UNIVERSITY OF NOVI SAD
Technical Faculty "Mihajlo Pupin"
Zrenjanin, Republic of Serbia

IIZS Conference

PROCEEDINGS

of the XV International Conference on

Industrial Engineering and Environmental Protection IIZS 2025

Zrenjanin, Serbia, October 2-3, 2025.



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INTRODUCTION

The Department of Mechanical Engineering and the Department of Environmental Protection of the Technical Faculty “Mihajlo Pupin” in Zrenjanin organized the XV International Conference on Industrial Engineering and Environmental Protection – IIZS 2025.

The topics of this scientific conference cover the fields of Industrial Engineering and Environmental Protection, including: Mechanical Engineering, Energetics and Process Technique, Design and Maintenance, Oil and Gas Engineering, Health and Environmental Protection, Environmental Management, and Occupational Safety.

The main goals of the conference are: encouraging innovation and broadening knowledge among engineers in industry and environmental protection; supporting researchers in presenting their current scientific results; establishing new connections with leading national and international institutions and universities; promoting the Faculty and its leadership role in society and the local community in order to attract high-quality young people to study at the Faculty; strengthening cooperation with other organizations, public enterprises, and industry; initiating the collection of ideas aimed at solving specific practical problems; enabling networking and the establishment of business contacts; presenting the results of scientific and technical research to professional and business organizations; and exchanging scientific knowledge and experiences in the field of industrial engineering.

We would like to express our sincere gratitude to the partners of the XV International Conference “IIZS 2025” – Aurel Vlaicu University of Arad, Faculty of Engineering, Arad, Romania; University St. Kliment Ohridski, Technical Faculty, Bitola, North Macedonia; University Politehnica Timisoara, Faculty of Engineering, Hunedoara, Romania; University of East Sarajevo, Faculty of Mechanical Engineering, East Sarajevo, Bosnia and Herzegovina, Republic of Srpska; and University of Giresun, Faculty of Engineering, Giresun, Turkey – for their support in organizing this event. We are also grateful to all authors who contributed their papers.

The IIZS Conference has become a traditional annual gathering of researchers from around the world. We are open to and thankful for all constructive suggestions that could help make the next, XVI International Conference on Industrial Engineering and Environmental Protection, even better in terms of organization and program content.

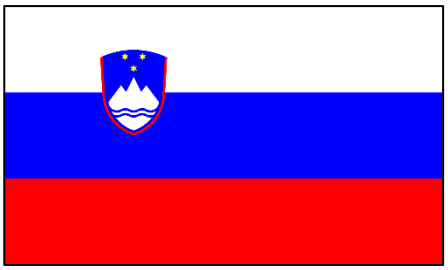
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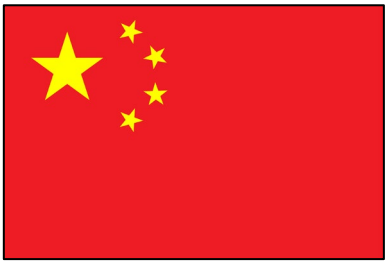
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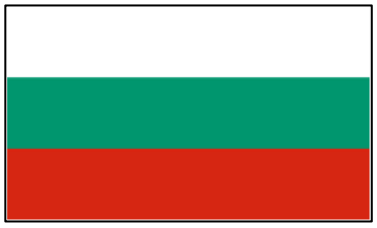
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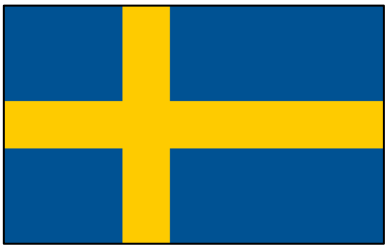
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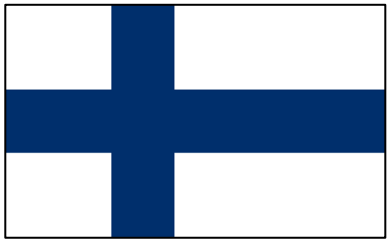
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MITIGATING TECHNICAL AND OPERATIONAL FAILURES IN THE DESIGN AND MAINTENANCE OF BIOGAS PLANTS

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Abstract: Biogas plants offer significant opportunities for sustainable rural development and diversification of energy supply, but recurrent technical and operational failures threaten their performance and long-term viability. This article systematically analyses the most common problems in construction, maintenance and operation, including structural defects, plant malfunctions and inadequate safety protocols. The focus of this study is to identify root causes - such as design flaws, material incompatibility and improper coordination of workflows - and to suggest advanced engineering and management solutions to prevent costly failures. By incorporating insights from actual case studies, the article offers practical recommendations for improving reliability, safety and profitability in modern biogas plants.
Key words: biogas plants, technical failures, design, construction, maintenance, operational risks, reliability

INTRODUCTION

Given the global rise in energy demand and worldwide efforts to reduce pollution, new, cleaner energy sources are becoming increasingly important. The World Bank predicts that high-income countries will see a 19% increase in daily per capita waste, while low- and middle-income countries will experience more than double that rise [1]. A major problem is that most of the world's agricultural waste is disposed of in unregulated landfills or burned openly. The use of organic waste for energy aligns with the principles of a circular economy and helps to reduce greenhouse gas emissions. Therefore, a growing number of studies and technological solutions are focused on sustainable energy sources, including energy derived from various biofuels such as ethanol and biogas [2]. In countries with substantial agricultural and livestock production, there is great potential for using environmentally friendly biogas technology as a renewable energy source [3]. In 2022, the total biogas production in the entire EU was 16.8 billion m3, and biomethane production was 4.2 billion m^3. These amounts are considered insufficient, and it is believed that the EU needs to increase production from these types of facilities. European countries commonly use biogas as a fuel in combined heat and power (CHP) units to generate both thermal and electrical energy, which is considered a highly efficient use of gas. Part of the produced electricity is used for the plant's own consumption, while the majority is supplied to the electrical grid [4]. The input material for bioenergy or biogas plants can be organic waste from agricultural and livestock production, as well as waste from the food processing industry, catering, and municipal sources [5]. A decade ago, Croatia promoted the production of electricity from biogas power plants and, through subsidies, invested over 331.81 million euros at the time, with owners of biogas plants investing even more. According to 2022 data, Croatia has 42 biogas plants and no biomethane plants. In that year, Croatia produced 0.11 billion m^3 of biogas, while the share of biogas in the natural gas supply in 2021 reached 4.1% [6]. Today, most of Croatia's biogas plants are in Slavonia, specifically in the Osijek-Baranja and Vukovar-Srijem counties, which have the largest number of farms [7]. Previous practices in Croatia point to several issues across all phases of bioenergy plant development, as well as with related legal regulations and market operations, all of which ultimately raise questions about their profitability and continued operation.
This paper identifies and analyzes specific shortcomings and errors in planning and design, construction, and maintenance of these plants. By implementing appropriate improvements, it

would be possible to achieve a significant reduction in the operating costs of these bioenergy plants. Recent research has focused on practical problems and technological solutions related to the planning, design, implementation, and operation of bioenergy plants. According to Saidmamatov et al. [8] biogas production can have a fivefold benefit by developing a local energy source, mitigating negative environmental impacts, reducing methane emissions, producing organic fertilizer as a byproduct, and providing additional income for farmers [8]. However, producing energy from biogas requires appropriate infrastructure, well-built and maintained facilities, as well as a transformation of the production practices in the sector that supplies the necessary organic materials [9]. The primary objective of a study by Singh et al. [10] was to highlight the practical challenges concerning the planning, design, monitoring and control systems, cost-benefit analysis, resource management, and optimization aspects for decentralized biogas plants, for which they conducted a comprehensive review of relevant literature. Activities both before and after the planning, design, and infrastructure development of decentralized biogas plants play a vital role in their sustainable and long-term operation [11]. Challenges in the pre-planning phase include conducting thorough feasibility studies and site assessments to identify an optimal location, as well as finding suitable raw material sources to ensure a consistent supply of organic waste [12]. Challenges related to post-planning activities encompass regular monitoring and maintenance, gas storage and utilization, securing a skilled workforce, and implementing safety measures such as managing odors and sludge, preventing gas leaks, and avoiding explosions [13]. Simultaneously, careful consideration of design and infrastructure development is also crucial for the smooth operation of these plants [14]. The main difficulties in this phase involve selecting the appropriate digester technology based on the availability of raw materials [15]. The use of poor-quality materials can compromise the structural integrity and longevity of a plant, leading to potential leaks, material degradation, and reduced efficiency [15,16]. Different technologies come with varying financial implications, and assessing long-term economic viability is essential for making informed decisions. Based on scientific and practical aspects, Gadirli et al. [2] conducted a study that focused on the design, construction, functioning, and operation of biogas plants in Poland. In their work on bioenergy production in Pakistan, Afridi and Qammar [3] identified problems in fundamental infrastructure, such as leaks from gas pressure, inadequate digestate removal, and a lack of a mechanism to prevent deposit formation and steel corrosion, and they proposed solutions.

TYPICAL BIOGAS PLANT SYSTEM

A biogas plant is a complex facility whose design depends on the type and quantity of raw materials used for biogas production (Fig. 1.).

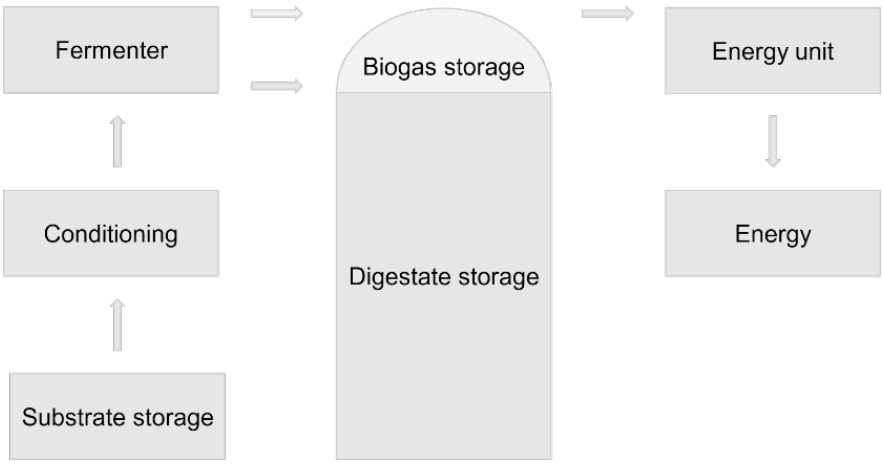


Fig. 1. *Biogas plant components diagram*

The main components of a typical biogas plant include: the feedstock reception and storage area, where raw materials like silage are received and stored. The digester is the most crucial

part of the plant, where raw materials are heated and mixed with water and microorganisms to produce and collect biogas. Other key parts are the biogas storage tank and the digestate storage unit, which holds the high-value organic fertilizer byproduct. The plant's operational infrastructure includes pump stations, as well as various pipelines, valves, and fittings to manage the flow of materials. The produced biogas is then converted into electrical and thermal energy in cogeneration units. The facility also contains a control unit for managing the process, a weighbridge, conveyors for material transport, and internal roads for logistics. Most structures are partially buried to accommodate pipelines that transport liquid feedstocks, digestate, and gas. These plants are typically built on large plots of land, often near rural areas, to connect to electricity and water supplies. Construction of a biogas plant is a demanding process, requiring the expertise of civil, mechanical, and electrical engineers. Challenges arise from working outdoors and from the increased construction demands for handling corrosive content. Heightened safety measures are essential to prevent potential explosions caused by the large quantities of methane produced during the process.

PLANNING AND DESIGN OF BIOGAS PLANT

This chapter outlines the key steps in building a biogas plant. These plants typically consist of a digester, and a secondary digester with identical dimensions. The process begins with planning the plant's layout and designing the digesters, which includes a methodology for determining their dimensions and those of the residue storage tanks. After site investigations, including soil analysis and groundwater levels, the facility layout for a commercial biogas plant can be planned. Following the planning phase, the project is undertaken, involving excavation, preparing the digester's base plate, and installing heating tubes, insulation, and other necessary technology [17]. The operation of the plant includes the use of various mechanical systems, such as a solids feeder, gas processing unit, and mixing technology. Finally, the system control is established, which allows for both remote and on-site monitoring of all individual facility components via a computer system. After site investigations, including soil analysis and groundwater levels, the facility layout for a commercial biogas plant can be planned. These plants typically consist of a digester, and a secondary digester with identical dimensions.

Attached to the digesters is a residue storage tank. The solids feeder is located next to the digester, and the entire tank area is surrounded by a green belt, except for one side where the horizontal silos are situated. Conventional digesters, also known as rural digesters, are used to process liquid raw materials with a high solids content and typically have a fermentation chamber volume of less than 100 m^3. In biogas plants, cylindrical, cast-in-place concrete or steel tanks are often used to store liquid manure. These tanks must be watertight to prevent groundwater pollution and rebar corrosion and are designed to withstand both the load of the soil surrounding the buried section and the weight of the stored liquid. The dimensions of these large, partially underground tanks typically range from 18 to 33 m in diameter, with heights from 2.4 to 4.9 m, and a uniform wall thickness of 150 to 200 mm [18]. The depth of digging depends on the specifications of the soil. For commercial biogas plants with large digesters reaching up to 25 meters in diameter, the concrete structure must be reinforced. To achieve this, standard 12-meter iron rods are cut and used to construct two iron grids, which are erected from the digester's base plate. Formwork, made from either wood panels or pre-constructed metal sheets, is then used to enclose the grids and create a container for the fluid concrete. Once the digester wall is built, approximately one-third of the internal surface is covered with a protective layer to prevent corrosion.

Biogas plants commonly feature two primary types of digesters, each offering distinct advantages depending on the project's needs. Metal digesters, often constructed from prefabricated glass-lined steel, are valued for their quick installation and consistent manufacturing quality. In contrast, concrete digesters (Fig. 2.) are built on-site and are a robust, durable solution typically chosen for large-scale projects, with designs that can be partially or fully buried underground for stability and thermal insulation. Glass-lined steel provides superior corrosion resistance to most acids and chemicals, allowing digesters to operate for many years

in extremely aggressive environments. However, this material is not without its challenges. At higher temperatures, glass becomes less effective against alkalis, and it is also very susceptible to impact damage during installation or operation. Such damage can create pinholes, which allow corrosive chemicals to attack the underlying steel. A major risk is that these defects can quickly lead to through-wall failures, resulting in the escape of liquid digestate or, more critically, methane gas. Methane can form an explosive mixture with air, which can be ignited by a spark from maintenance or static electricity. Because welding is too risky and can damage the glass lining, costly repairs must be performed using alternative solutions that cure at ambient temperatures, such as epoxy composites or prefabricated non-metallic patches.



Fig. 2. *Circular concrete digester*

In concrete anaerobic digesters, complications can arise from a cold start, before necessary bacteria are established, or when the digester is taken out of service, introducing oxygen and upsetting the pH. The presence of undigested volatile acids can also lower the pH and kick-start corrosion. When these issues occur, they primarily impact the biogas phase and the surface of the effluent substrate. Corrosion is caused by moisture reacting with contaminants like hydrogen sulfide (H_2S) to generate highly corrosive sulfuric acid. This acid attacks the vapor space at the top of the tank, the walls, the underside of the roof, and the internal pipework. Given that aging digesters require robust corrosion management strategies, non-metallic solutions like high-performance coatings have proven to be effective in extending an asset's lifetime and reducing maintenance.

The construction of a gas holder begins with building an umbrella-shaped wood or steel structure, over which a mesh network is laid. An air-supported double-membrane cover, which includes the gas holder, is then mounted over this structure. The inner flexible membrane of the gas holder is designed to move up and down in response to changes in gas pressure.

The technology installation phase involves setting up the essential internal components first, such as the filling indicator, tubes, measuring devices, and the electricity and fiber cable networks. Following this, the gas collector is installed along with the excess and low-pressure safeguards and the air support fan. This is the process of insulating the digester, which is a critical construction step that should be performed carefully and accurately. The digester is lined with either mortar containing 1% silica, followed by a coat of petroleum albumen, or with foam sheets. In other designs, the walls are heat-insulated with non-corroding and weather-proof aluminum trapezoidal panels. In contrast, rural digesters are typically coated with layers of dry dirt and asbestos.

However, once these assets are built, a new set of challenges arises. Despite the best construction practices, the operational environment of a biogas plant is extremely aggressive. When designing biogas plants, safety issues are just as vital as technological aspects. The system's elements must be arranged to prevent the domino effect, where damage to one element leads to a fire that affects others. For instance, low-pressure tanks require a minimal distance of 9 meters from other elements, while high-pressure tanks need at least 50 meters

due to thermal radiation risks. Similarly, zones where flammable gas concentrations exceed safe limits must be free of ignition sources.

CLASSIFYING COMMON SOURCES OF HAZARDS AND INCIDENTS IN BIOGAS PLANTS

Common sources of hazards in biogas plants

This chapter provides an overview of the main sources of hazards in biogas plants. The history of failures and accidents in biogas plants demonstrates that the total elimination of hazards in this sector is not feasible. However, it is possible to influence some of the hazards during the construction process itself, with examples of poorly executed works presented in Table 1.

Table 1. *Common hazards in biogas plants: failures due to construction*

Hazard	Failures due to construction	Consequences
Fire and explosion	Instability of the gas storage components, incorrect assembly of gas storage elements, unevenness on the concrete crown of the storage tank	 
Biohazard	Improper and insufficiently executed protection and waterproofing of surfaces through which dangerous substances penetrate into the soil—floors and walls of the storage tank, fermenter (digester), lagoon	 
Electric	Improper execution and protection of electrical installations, penetration of moisture and water into areas where the installations are located	 

Mechanical	Improperly prepared foundation and installation for positioning mechanical equipment, as well as pipes that transport raw materials, gas, and digestate	 

Although biogas production has significant environmental benefits, these facilities involve risks related to fires, explosions, and biological and mechanical hazards. These hazards will now be described, covering those that are possible during the exploitation of a biogas plant. For a better overview, Table 2 with the listed hazards, their causes, and mitigation techniques is provided [19].

Table 2. *Sources of hazards in biogas plants, their contributing factors, and mitigation techniques*

Hazard	Contributing factors	Mitigation technique
Fire and explosion	The risk of a fire or explosion, exist when the concentration of methane in the air is within the range of 5% to 15%	Monitoring and control Ignition source control System design and maintenance
Biohazard	Presence of microorganisms, such as bacteria, viruses, fungi, and parasites, in the organic waste feedstock	Monitoring and control Hygiene standards Disinfection
Electric	Electrical equipment that is not properly installed or maintained	Regulations and standards Design and installation Maintenance
Mechanical	Frequent use of heavy gear and equipment with moving parts	Proper machine guarding Regular maintenance Adequate training

Biogas is a flammable gas that presents a fire and explosion risk if it encounters a spark or flame. Mixtures of air and methane pose a particular danger and can ignite at a methane concentration between 5% and 15%. Under ideal conditions, when the mixture is near its stoichiometric ratio, a powerful explosion can occur, making it crucial to monitor and manage gas concentration within the plant. Biohazards stem from the nature of the raw materials used, including manure, food waste, and sewage sludge. These materials can contain various microorganisms like bacteria, viruses, and fungi that can threaten workers' health, potentially causing gastrointestinal illnesses or skin and respiratory infections. To prevent these risks, it is essential to use appropriate personal protective equipment, adhere strictly to hygiene standards, and perform regular disinfection of equipment and work areas. Mechanical hazards at the plants are significant due to the use of heavy equipment and moving parts. Workers are at risk of crushing, entanglement, and amputation injuries. It is vital to carefully assess and mitigate these risks through proper machine guarding, regular maintenance and inspections, and providing adequate training for staff. Electrical hazards are present due to the extensive use of electrical equipment. Improper installation or maintenance can lead to electric shock or fire. Because of this, strict standards and regulations have been developed by international organizations and national governments. These regulations ensure the safe design, installation, operation, and maintenance of electrical systems, thereby protecting workers and the environment.

Common causes of incidents

Incidents in biogas plants, which can range in severity, are typically caused by a variety of factors. These can include human errors in operations and maintenance, equipment and component failures, and natural or technological disasters. The severity of these incidents, which can manifest as accidents, is determined by factors such as the type and location of the event, as well as the effectiveness of the existing safety measures [19]. Accidents in the biogas sector are typically caused by equipment and component failures, design errors, and improper operation or maintenance. Across the broader bioenergy sector, a majority of accidents are a result of fires (53%) and explosions (40%), with a smaller percentage (7%) related to toxic releases [20].

As previously mentioned, accidents can be the result of a combination of various factors, including maintenance error, equipment failure, operational error, component failure, and natural disasters (Table 3).

Table 3. *Common types of accidents and their descriptions*

Accident	Description
Maintenance error	Improperly inspecting or replacing equipment. Regular maintenance is essential for safe and efficient operation
Equipment failure	Leaks or malfunctions (electric and mechanical hazards), can occur, resulting in occurrences and injuries
Operational error	Misinterpreting data or failing to follow proper protocols can lead to significant causes of biogas plant occurrences
Component failure	Component failure is a common cause. Parts can fail due to normal wear and tear, corrosion, and fatigue
Natural occurrences	Natural occurrences such as floods, earthquakes can cause equipment damage or structural failures

Since biogas plants are a relatively new type of industrial facility, safety regulations for them have not been fully developed [21]. Understanding the range of hazards and causes of accidents in biogas plants is essential for ensuring safety. It is also important to recognize that the unique variables of biogas facilities can make their occurrences distinct from those in other industries. Therefore, further research is needed to overcome the challenges of data underreporting and to establish clearer causal relationships to continue to enhance safety protocols.

CONCLUSION

The construction and operation of a biogas plant is a highly complex process, requiring diverse expertise and facing an extremely aggressive operating environment that threatens material integrity. While biogas production offers significant environmental benefits, the inherent nature of the process means the complete elimination of hazards is not feasible. Risks such as fire, explosion, biohazards, and mechanical/electrical failures are constantly present, often stemming from design flaws, equipment failure, or human error.

Although biogas plants are conceived as a smart and ecological way to manage waste and generate environmental profit, they can sometimes turn into the site of ecological and material disasters. The most crucial element throughout the entire process of plant construction and operation is the human factor. Project designers and contractors bear immense responsibility, as irregularities in execution can significantly contribute to poor operating outcomes.

To ensure both safety and long-term viability, a proactive strategy is essential. This includes careful analysis of system element placement during design to prevent cascade failures, employing effective mitigation techniques (like gas content monitoring and regular

maintenance), and upgrading existing technological options. Furthermore, the successful implementation of biogas projects requires an integrated approach to managing the entire supply chain and logistics, alongside crucial investment in training programs for technicians and operators to ensure the availability of a skilled workforce for long-term success.

REFERENCES

[1] Issahaku, M., Derkyi, N.S.A., Kemausuor, F., A systematic review of the design considerations for the operation and maintenance of small-scale biogas digesters, Heliyon, Vol.10, 2024.
[2] Gadirli, G., Pilarska, A.A., Dach, J., Pilarski, K., Kolasa-Więcek, A., Borowiak, K., Fundamentals, operation and global prospects for the development of biogas plants — A review, Energies, Vol.17, p.568, 2024.
[3] Afridi, Z.U.R., Qammar, N.W., Technical challenges and optimization of biogas plants, ChemBioEng Reviews, Vol.7, pp.119–129, 2020.
[4] Raff, R., Biogas cogeneration unit for electrical and thermal energy production, Proceedings of OTO, Osijek, pp.199–205, 2017.
[5] Lozančić, S., Popović, I., Problemi u gradnji proizvodnih postrojenja, Zbornik radova 13. susreta Hrvatskog društva za mehaniku, Zagreb, pp.125–130, 2024.
[6] Odorčić, B., Bioplin više nije neželjeno dijete, Energetika-net.com, accessed September 8, 2025.
[7] Alilović, I., Proizvođači u velikim problemima: Inspekcije obilaze I zatvaraju bioplinskapostrojenja, Glas Slavonije, accessed September 8, 2025.
[8] Saidmamatov, O., Rudenko, I., Baier, U., Khodjaniyazov, E., Challenges and solutions for biogas production from agriculture waste in the Aral Sea Basin, Processes, Vol.9, p.199, 2021.
[9] Pilarska, A., Pilarski, K., Operation and challenges of biogas technology: A fundamental overview, Technical Sciences, Vol.27, 2024.
[10] Singh, D., Tembhare, M., Dikshit, A.K., Dangi, M.B., Kumar, S., Technical and operational challenges in setting up a decentralized biogas plant: Opportunities and future perspective toward sustainable nation, Process Safety and Environmental Protection, Vol.185, pp.392–407, 2024.
[11] O'Connor, S., Ehimen, E., Pillai, S.C., Black, A., Tormey, D., Bartlett, J., Biogas production from small-scale anaerobic digestion plants on European farms, Renewable and Sustainable Energy Reviews, Vol.139, 110580, 2021.
[12] Yalcinkaya, S., A spatial modeling approach for siting, sizing and economic assessment of centralized biogas plants in organic waste management, Journal of Cleaner Production, Vol.255, 2020.
[13] Zábranská, J., Dohányos, M., Jeníček, P., Zaplatílková, P., Kutil, J., The contribution of thermophilic anaerobic digestion to the stable operation of wastewater sludge treatment, Water Science and Technology, Vol.46, pp. 447–453, 2002.
[14] Teixeira Franco, R., Buffière, P., Bayard, R., Optimizing storage of a catch crop before biogas production: Impact of ensiling and wilting under unsuitable weather conditions, Biomass and Bioenergy, Vol.100, pp. 84–91, 2017.
[15] Khan, E.U., Martin, A.R. Review of biogas digester technology in rural Bangladesh, Renewable and Sustainable Energy Reviews, Vol.62, pp. 247–259, 2016.
[16] Mirmohamadsadeghi, S., Karimi, K., Tabatabaei, M., Aghbashlo, M., Biogas production from food wastes: A review on recent developments and future perspectives, Bioresource Technology Reports, Vol.7, 2019.
[17] Kumar, S., editor, Biogas, IntechOpen, 2012.
[18] Ghafoori, E., Flynn, P.C., Optimizing the logistics of anaerobic digestion of manure, Appl Biochem Biotechnol, Vol.137–140, pp. 625–637, 2007.
[19] Hegazy, H., Saady, N.M.C., Khan, F., Zendehboudi, S., Albayati, T.M., Biogas plants accidents: Analyzing occurrence, severity, and associations between 1990 and 2023, Safety Science, Vol.177, 2024.

[20] Stolecka, K., Rusin, A., Potential hazards posed by biogas plants, Renewable and Sustainable Energy Reviews, Vol.135, 2021.
[21] Winquist, E., Van Galen, M., Zielonka, S., Rikkonen, P., Oudendag, D., Zhou, L., Greijdanus, A., Expert Views on the Future Development of Biogas Business Branch in Germany, The Netherlands, and Finland until 2030, Sustainability, Vol.13, 2021.



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Session 1

Mechanical Engineering

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DYNAMIC STABILITY OF A SLIGHTLY CURVED PIPE RESTING ON A WINKLER ELASTIC FOUNDATION

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Abstract: This article investigates the stability of a slightly curved pipe conveying fluid, which is supported by a Winkler elastic foundation and fixed (cantilevered) at its left end. The Galerkin method is employed to solve this problem. The primary goal is to determine how the rigidity of the Winkler elastic foundation and the density of the fluid being conveyed affect the critical fluid velocity – the velocity at which the pipe becomes unstable. The numerical analysis presented in this work includes graphs that illustrate how the critical fluid velocity changes with the rigidity of the Winkler elastic foundation for various fluid densities. The results show that the stability of the system is influenced by both the elastic foundation's rigidity and the conveyed fluid's density.
Key words: Slightly curved pipes, Fluid, Critical velocity, Dynamic stability, Winkler elastic foundation, Galerkin method

INTRODUCTION

In engineering practice, a frequently used model for the soil foundation due to its simplicity is the Winkler model. In this model, the elastic foundation is modeled by a multitude of closely spaced linear springs.
Lotati and Kornecki [1] considered a clamped pipe resting on a Winkler elastic foundation, as well as a pipe simply supported at both ends. They proved that in both cases, the elastic foundation has a stabilizing effect. This effect manifests as an increase in the critical fluid velocity.
In 1970, Stein and Tobriner [2] also studied the vibrations of a pipe conveying fluid and resting on a Winkler elastic foundation.
P. Dzhondzhorov [3] investigated the stability of a pipeline clamped at one end and resting on an elastic foundation whose stiffness varies according to a linear law as a function of the axial coordinate. Linear functions for which the loading diagrams have equal areas were considered. It was established that for all such functions, the elastic foundation has a stabilizing effect on the pipeline. For a foundation where the stiffness variation is represented by a triangle with the maximum value of the Winkler elastic foundation coefficient at the free end of the pipe, this effect is the greatest. It was found that with an increase in the slope of the linear stiffness function of the soil foundation, its stabilizing effect also increases.
Other studies in the field of pipelines resting on an elastic foundation with varying stiffness were carried out by P. Dzhondzhorov, V. Vasilev, and V. Dzhupanov [4]. They considered a clamped pipe resting on an elastic foundation. The stiffness of the elastic foundation varies according to a quadratic parabola. The obtained critical velocities were compared with the critical velocities for the same pipe but without the presence of an elastic foundation. It was proven that the elastic foundation has a stabilizing effect on the system.
P. Dzhondzhorov [5] investigated the influence of a Winkler elastic foundation, applied to a part of the pipeline, on the dynamic stability of a clamped pipe conveying fluid. The author studied how the critical velocity of the conveyed fluid changes depending on the length and position of the section with the elastic foundation, as well as according to the stiffness of the foundation. The studies show that the elastic foundation can have a stabilizing or destabilizing effect on the system.
Sv. Lilkova-Markova [6] investigated the dynamic stability of a pipeline with flowing fluid. One end is free, and the other is clamped, simply supported, or free. A part of the pipeline rests on a Winkler elastic foundation. In all considered cases, the critical velocity of the flowing fluid was determined.

A recent study [7] examined the stability of fluid-conveying pipes supported by a two-parameter elastic foundation. Using the Euler-Bernoulli beam model under various boundary conditions, the authors applied the Differential Transform Method. Their findings show that the elastic foundation contributes to system stability, and increasing its parameters raises the critical flow velocity.
In a further recent investigation [8], the dynamic stability of a cantilevered pipe subjected to a lateral distributed load was analyzed. The Differential Quadrature Method was utilized in the analysis.
Ding and Ji [9] provide an extensive overview of recent advancements in vibration control techniques for fluid-conveying pipes.
The broad applications of nanoscale tubes in both scientific and industrial contexts have driven significant research efforts, as noted in [10] and [11]. To address the challenges and high costs associated with nanoscale experimentation, studies on fluid-structure interaction in carbon nanotubes often rely on continuum elastic models, including Euler and Timoshenko beam theories.

PROBLEM FORMULATION

The differential equation describing the transverse vibrations of an Euler-Bernoulli pipe with an initial geometric imperfection resting on the Winkler elastic foundation (Fig.1) is as follows [12]:

$$EI\frac{\partial^4 w}{\partial x^4}+\left(m_f+m_p\right)\frac{\partial^2 w}{\partial t^2}+2m_f V\frac{\partial^2 w}{\partial t\,\partial x}+m_f V^2\frac{\partial^2 w}{\partial x^2}+$$
$$+kw=\frac{EA}{l}\int_0^l\left[\frac{dZ}{dx}\frac{\partial w}{\partial x}+\frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^2\right]dx\left(\frac{\partial^2 w}{\partial x^2}+\frac{d^2 Z}{dx^2}\right), \tag{1}$$

where EI is the bending rigidity and EA is the axial rigidity of the pipe, m_f is the mass of the fluid per unit length of the pipe, m_p is the mass of the pipe per unit length, k is the rigidity of the Winkler elastic foundation, x is the longitudinal coordinate along the pipe axis, t is the time and l is the length of the pipe. $w(x,t)$ is the transverse displacement of the pipe's cross-section. The remaining system characteristics are the velocity of the conveyed fluid V and the function of the initial imperfection of the axis of the pipe $Z(x)$.

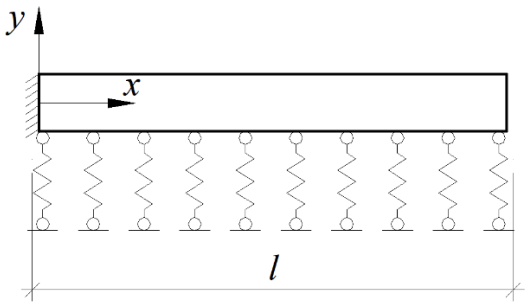


Fig. 1. *Static scheme of the pipe*

The assumption of a small rise to span ratio implies that a geometrically imperfect pipe is effectively a shallow arch [12].
In the present study for the function of initial imperfection $Z(x)$ is chosen a sinusoidal function satisfying the boundary conditions of the pipe depicted in Fig.1

$$Z(x) = b(1 - \cos x) \tag{2}$$

The boundary conditions for a cantilevered at its left end pipe (Fig.1) are as follows:

$$w(0,t) = 0 \text{ and } \frac{\partial w(0,t)}{\partial x} = 0 \tag{3}$$

To facilitate the analysis, the equation is non-dimensionalized by defining the following terms:

$$\eta = \frac{w}{r}; \xi = \frac{x}{l}; z = \frac{Z}{r}; u = Vl\sqrt{\frac{m_f}{EI}}; \beta = \frac{m_f}{m_f + m_p}; \tau = \frac{t}{l^2}\sqrt{\frac{EI}{m_f + m_p}}; \bar{k} = \frac{kl^4}{EI} \tag{4}$$

In (4) r represents the radius of gyration of the cross-section on the pipe.
The non- dimensional form of the differential equation (1) is as follows:

$$\frac{\partial^4 \eta}{\partial \xi^4} + u^2 \frac{\partial^2 \eta}{\partial \xi^2} + 2\sqrt{\beta} u \frac{\partial^2 \eta}{\partial \tau \partial \xi} + \frac{\partial^2 \eta}{\partial \tau^2} + \bar{k}\eta - \int_0^1 \left[\frac{dz}{d\xi}\frac{\partial \eta}{\partial \xi} + \frac{1}{2}\left(\frac{\partial \eta}{\partial \xi}\right)^2 \right] d\xi \left(\frac{\partial^2 \eta}{\partial \xi^2} + \frac{d^2 z}{d\xi^2} \right) = 0 \tag{5}$$

After the transformation to dimensionless variables, the boundary conditions (3) become:

$$\eta(0,\tau) = 0 \text{ and } \frac{\partial \eta(0,\tau)}{\partial \xi} = 0 \tag{6}$$

To solve this differential equation (1), the Galerkin method is applied.
The functions $\eta(\xi,\tau)$ is sought in the following form:

$$\eta(\xi,\tau) = \sum_{i=1}^{n} q_i(\tau) y_i(\xi) \tag{7}$$

In (7) $q_i(\tau)$ are generalized coordinates and $y_i(\xi) = \frac{Y_i(x)}{r}$ are basis functions, where $Y_i(x)$ are the eigenfunctions of the pipe. For the pipe in Fig.1 the eigenfunctions $Y_i(x)$ have the following form [13]

$$Y_i(x) = A_i \left[\sin\frac{\lambda_i x}{l} - \sinh\frac{\lambda_i x}{l} - \frac{\sin\lambda_i + \sinh\lambda_i}{\cos\lambda_i + \cosh\lambda_i}\left(\cos\frac{\lambda_i x}{l} - \cosh\frac{\lambda_i x}{l} \right) \right] \tag{8}$$

where $\cos\lambda_i \cosh\lambda_i + 1 = 0$ and $\lambda_i < \lambda_{i+1}$, $i = 1,2,...,n$. The constants A_i are chosen so that the eigenfunctions are orthogonal. The condition for orthogonality of the functions is represented by the following expression:

$$\int_0^l Y_i(x) Y_k(x) dx = \delta_{ik} \tag{9}$$

In (9) δ_{ik} is Kronecker delta.

Since expression (7) is not the exact solution of the differential equation (1), substituting (7) into (1) results in a residual function $R(\xi,\tau)$.

$$\sum_{i=1}^{n}\left\{\frac{\partial^4 y_i}{\partial\xi^4}q_i + y_i\ddot{q}_i + 2u\sqrt{\beta}\frac{\partial y_i}{\partial\xi}\dot{q}_i + u^2\frac{\partial^2 y_i}{\partial\xi^2}q_i + \right.$$
$$\left. +\bar{k}\,y_i q_i - \int_0^l\left[\frac{dz}{d\xi}\frac{\partial y_i}{\partial\xi}q_i + \frac{1}{2}\left(\frac{\partial y_i}{\partial\xi}q_i\right)^2\right]d\xi\left(\frac{\partial^2 y_i}{\partial\xi^2}q_i + \frac{d^2 z}{d\xi^2}\right)\right\} = R(\xi,\tau), \tag{10}$$

The Galerkin method determines the unknown functions $q_i(\tau)$ by minimizing the residual function $R(\xi,\tau)$ over the region $\xi\in[0;1]$. This condition is expressed as:

$$\int_0^1 R(\xi,\tau)y_k(\xi)d\xi = 0; \quad k = 1,...,n \tag{11}$$

The condition (11) represents the requirement that the residual function $R(\xi,\tau)$ has to be orthogonal to all basis functions $y_i(\xi)$. Substituting (10) into (11) leads to a system of n differential equations with respect to the unknown functions $q_i(\tau)$. This system has the following expression:

$$\sum_{i=1}^{n}\int_0^1\left\{\frac{\partial^4 y_i}{\partial\xi^4}q_i + y_i\ddot{q}_i + 2u\sqrt{\beta}\frac{\partial y_i}{\partial\xi}\dot{q}_i + u^2\frac{\partial^2 y_i}{\partial\xi^2}q_i + \right.$$
$$\left. +\bar{k}\,y_i q_i - \int_0^l\left[\frac{dz}{d\xi}\frac{\partial y_i}{\partial\xi}q_i + \frac{1}{2}\left(\frac{\partial y_i}{\partial\xi}q_i\right)^2\right]d\xi\left(\frac{\partial^2 y_i}{\partial\xi^2}q_i + \frac{d^2 z}{d\xi^2}\right)\right\}y_k d\xi = 0, \tag{12}$$

These nonlinear differential equations can be solved using the seventh-eight order continuous Runge-Kutta method.
The non-linear dynamical behavior of the system is investigated based on the bifurcation diagrams.

RESULTS AND DISCUSSION

This paper investigates the influence of the Winkler elastic foundation's rigidity on the stability of the system by employing the Galerkin method, as detailed in the preceding section. Numerical simulations are conducted for the beam depicted in Fig. 1. The system's material and geometric properties include: the modulus of elasticity of the pipe material $E = 210\,GPa$, the density of the pipe's material $\rho = 7800\,kg/m^3$, the outer and inner radii of the pipe's cross-section ($R_{out} = 0.014\,m$ and $R_{in} = 0.012\,m$, respectively), and the mass ratio $\beta = 0,3$.
The bifurcation diagram for the right end cross-section of the pipe is shown in Figure 2. This diagram was generated using $\bar{k} = 30$, with the following initial conditions for the cross-section: $\eta(1,0) = 10^{-6}$ and $\dot{\eta}(1,0) = 10^{-4}$. The Hopf bifurcation point signifies the loss of system stability, and the corresponding velocity $u_{cr} = 3,25$ is termed the critical velocity. Although a second bifurcation point appears at $u_{cr} = 4,34$, the first critical velocity holds the primary practical significance.

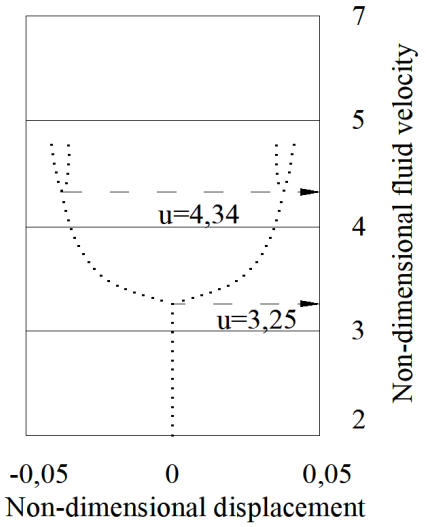


Fig. 2. *Bifurcation diagram of the right end cross-section for* $\beta = 0{,}3$ *and* $\bar{k} = 30$

Figure 3 illustrates the relationship between the non-dimensional critical velocity u_{cr} and the dimensionless rigidity of the Winkler elastic foundation $\bar{k}$ for two different mass ratios β.

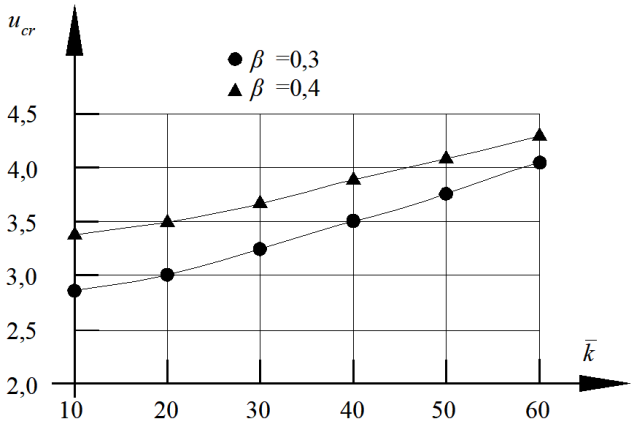


Fig. 3. *The relation between the non-dimensional critical velocity* u_{cr} *and the dimensionless rigidity of the Winkler elastic foundation*

CONCLUSIONS

In this paper, a slightly curved pipe conveying fluid and resting on a Winkler elastic foundation was investigated. The differential equation describing the lateral vibration of the pipe was solved using the Galerkin method, a widely used and powerful fundamental tool for the numerical solution of differential equations. The most crucial aspect of obtaining a solution through this method is the careful selection of the number of modes to include in the approximate solution, ensuring that the neglected modes do not significantly affect the solution's precision [12].
Based on the numerical investigations presented in this article, several major conclusions can be made.

- Figure 2 illustrates the findings of the numerical analysis, revealing that the pipe's stability could be compromised via a Hopf bifurcation, with subsequent bifurcations also occurring.

- The diagram in Figure 3 demonstrates that for the pipe under study, a stiffer Winkler elastic foundation enhances the system's stability, leading to higher critical fluid velocities.
- Numerical studies also suggest that a larger mass ratio β contributes to stabilizing the system.

REFERENCES

[1] Lottati, I., Kornecki, A., The Effect of an Elastic Foundation and of Dissipative Forces on the Stability of Fluid-Conveying Pipes, Journal of Sound and Vibration, vol. 109, pp. 327-338, 1986.
[2] Stein, R., Tobriner, M., Vibrations of Pipes Containing Flowing Fluids, Transactions of the ASME, Journal of Applied Mechanics, vol.37, pp. 906-916, 1970.
[3] Djondjorov, P., On the Critical Velocities of Pipes on Variable Elastic Foundation, Journal of Theoretical and Applied Mechanics, vol. 31, no. 3, pp. 73-81, 2001.
[4] Djondjorov, P., Vassilev, V., Dzhupanov, V., Dynamic Stability of Fluid Conveying Cantilevered Pipes on Elastic Foundations, Journal of Sound and Vibration, vol. 247, no. 3, pp. 537-546, 2001.
[5] Djondjorov, P., Dynamic Stability of Pipes Partly Resting on Winkler Foundation, Journal of Theoretical and Applied Mechanics, vol. 31, no. 3, pp. 101-112, 2001.
[6] Lilkova-Markova, Sv., Influence of the Elastic Foundation on the Dynamic Stability of Fluid-Conveying Pipes Under Three Support Conditions, Proceedings of the Anniversary Scientific Conference 60 Years UACEG, pp. 339-344, 2002.
[7] Balkaya M., Kaya M., Analysis of the instability of pipes conveying fluid resting on two-parameter elastic soil under different boundary conditions, Ocean Engineering, vol.241, pp.110003, 2021.
[8] Zhang Yu, Pengzhou Li, Dynamical stability of pipe conveying fluid with various lateral distributed loads, Archive of Applied Mechanics, vol.93, pp. 4093-4106, 2023.
[9] Ding Hu, Ji J., Vibration control of fluid-conveying pipes: A state of the art review, Appl.Math.Mech.-Engl., vol. 44, pp. 1423-1456, 2023.
[10] Xueping C., Xiaoxiang H., Congjia Q., Yinghui L., Stability and nonlinear vibration of carbon nanotubes-reinforced composite pipes conveying fluid, Ocean Engineering, vol.281, pp. 114960, 2023.
[11] Vassilev V., Valchev G., Dynamics and stability of Double-Walled Carbon Nanotube cantilevers conveying fluid in an elastic medium, Dynamics, vol. 4, no.2, pp. 222-232, 2024
[12] Sinir, B.G., Bifurcation and Chaos of Slightly Curved Pipes, Mathematical and Computational Applications, vol. 15, no. 3, pp. 490-502, 2010.
[13] Djondjorov, P., Vassilev, V., Dzhupanov, V., Dynamic Stability of Fluid Conveying Cantilevered Pipes on Elastic Foundations, Journal of Sound and Vibration, vol.247, no. 3, pp. 537-546, 2001.

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THERMOGRAPHIC ASSESSMENT OF PRESSURE RELIEF VALVE OPERATION

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Abstract: This paper presents a thermographic investigation of the Bowen HR560 coiled tubing unit, used in drilling operations in oilfield applications. The unit enables well interventions using coiled tubing, including pressure control via safety valves. The aim of this study was to assess the operational condition and detect potential malfunctions in the unit, particularly around the pressure relief valve, using thermography as a non-invasive diagnostic method. An infrared camera was employed to identify thermal anomalies, such as localized overheating, which may indicate mechanical faults, inadequate lubrication, or excessive operating pressure.The obtained thermograms were compared with reference thermal profiles to detect deviations and potential indicators of operational issues. The results demonstrate that thermography is an effective tool for early fault detection and for maintaining the operational reliability of coiled tubing units, thereby contributing to safety and uninterrupted performance in well intervention operations.
Key words: Coiled tubing unit, pressure relief valve, thermography.

INTRODUCTION

In modern technical systems, early detection of potential failures represents a key factor in maintaining reliability, safety, and operational efficiency. The application of diagnostic tools and methods enables timely detection of anomalies, thereby preventing failure escalation, reducing the costs of unscheduled maintenance, and minimizing downtime. In this context, the systematic integration of fault detection and diagnostic algorithms—ranging from traditional methods such as Failure Modes and Effects Analysis (FMEA) and Root Cause Analysis (RCA) to advanced AI-driven techniques, has become fundamental for the development of more resilient and self-adaptive technical systems, [1-5].
Complex systems, often operating under functional, safety, and economic constraints, must be equipped with tools that enable continuous monitoring of their condition. Sensor data (vibration, thermal, ultrasonic, etc.), combined with model-based and data-driven approaches, enable not only fault detection but also fault prediction, thereby facilitating the transition from reactive to proactive maintenance, so-called predictive maintenance. Such systems not only extend the operational lifespan of equipment but also enhance safety and optimize the utilization of resources, [6-9].
In the field of technical diagnostics, thermography stands out as a method that enables system inspection under real operating conditions without the need to interrupt processes, thereby minimizing operational losses. The identification of localized zones of elevated temperature often indicates mechanical defects (e.g., faulty bearings, inadequate lubrication), electrical faults (e.g., increased contact resistance, conductor overloading), or inefficient heat transfer processes (e.g., thermal bridges, degraded insulation), [10-12].
The industrial application of thermography encompasses a wide range of sectors and operational scenarios. In power systems, it is used for the preventive detection of anomalies in transformers, disconnectors, circuit breakers, and conductors, thereby reducing the probability of catastrophic failures and extending the service life of components. In the machinery industry, thermographic inspection of power units, rotating machines, and transmission assemblies enables early detection of irregularities in tribological pairs and cooling systems. In the process and chemical industries, it is applied to detect fluid leakages, identify non-uniform temperature distributions in reactors and heat exchangers, and optimize the energy efficiency of facilities.

Within modern predictive and proactive maintenance concepts, thermography is integrated with data acquisition systems, IoT networks, and machine learning algorithms, enabling automated processing of large volumes of thermal data and the development of adaptive models for equipment condition assessment. This approach contributes to increased reliability, reduced life-cycle costs, and enhanced operational safety, making thermography an indispensable diagnostic tool in Industry 4.0 and future smart manufacturing systems.
In addition to protecting pumps, pipes, couplings, and actuator components from overload, pressure relief valves ensure system operational stability by maintaining optimal pressure conditions during load variations or unforeseen operational disturbances.
In modern hydraulic systems, pressure relief valves are designed with a high degree of precision and reliability, often featuring fine pressure adjustment capabilities and integration with electronic monitoring systems. They vary in design and operation—from direct-acting valves, which respond rapidly to pressure spikes, to pilot-operated valves, which provide more stable operation under high flow rates and elevated pressures. Proper selection, sizing, and maintenance of these valves are essential for the longevity and safe operation of hydraulic systems, particularly in high-pressure industries such as oil and gas, construction, and process engineering, [13-16].
The Bowen HR560 is a mobile coiled tubing unit (CTU) manufactured by Bowen, designed for conducting various well intervention operations. This unit is intended for efficient execution of well testing, cleaning, stimulation, and other procedures requiring the use of coiled tubing.The unit is composed of three primary components. The first is a tractor equipped with a hydraulic system, providing the necessary power to operate all systems within the unit. The second component is a trailer containing a control cabin, a tubing reel system, and an injector. The reel system is integrated through the trailer to maintain a legally permissible road transport height, while the injector is mounted on an incline behind the reel, ensuring tubing stability during transport and operational deployment. The third component is a crane with a track, enabling precise handling of equipment and tools during well interventions.This configuration provides a high level of operational flexibility and efficiency, making the Bowen HR560 a suitable solution for modern oil and gas industries that require precise and reliable application of coiled tubing technology.

MATERIAL AND METHODS

For the purposes of this study, the mobile coiled tubing unit Bowen HR560 was employed, equipped with standard hydraulic pressure relief valves that regulate the system's maximum operating pressure and protect components from overload. The valves were selected according to the manufacturer's recommendations and included both direct-acting and pilot-operated types, allowing for the examination of various operational characteristics under varying pressures and flow rates. For thermographic analysis, a Testo high-resolution infrared (IR) camera with a temperature range of -20 °C to 500 °C and an accuracy of ±2 °C was used. The camera was calibrated prior to the experiments to ensure reliable and reproducible measurements of the valves' thermal characteristics. In addition to the IR camera, standard hydraulic instruments for measuring pressure and flow, as well as safety equipment necessary for high-pressure operations in field conditions, were utilized.
Testing was conducted under real operational conditions in a workshop, during which the pressure relief valves of the Bowen HR560 unit were subjected to standard operational cycles. The IR camera was positioned to enable continuous monitoring of the valves' thermal profiles during load variations and pressure increases.
Thermal images were captured at 10-second intervals, and the collected data were analyzed using a thermography software package, including the generation of temperature maps and the identification of potential overheating zones. This approach enabled the detection of anomalies in valve operation, such as localized temperature increases due to overload or reduced efficiency in pilot-operated valves.
The results were further corrected for ambient temperature and the emissivity of the valve materials, ensuring precise quantification of thermal characteristics. The combination of

thermographic analysis and standard hydraulic measurements allowed for a detailed assessment of valve performance and the identification of potential critical points within the Bowen HR560 hydraulic system.

RESULTS OF INSPECTION AND DISCUSSION

The recording and inspection were conducted over a period of three machine operating hours, during which the gradual heating of all components of the Bowen HR560 system was monitored. Fig. 1 shows the initial temperatures during the so-called cold operation of the machine.

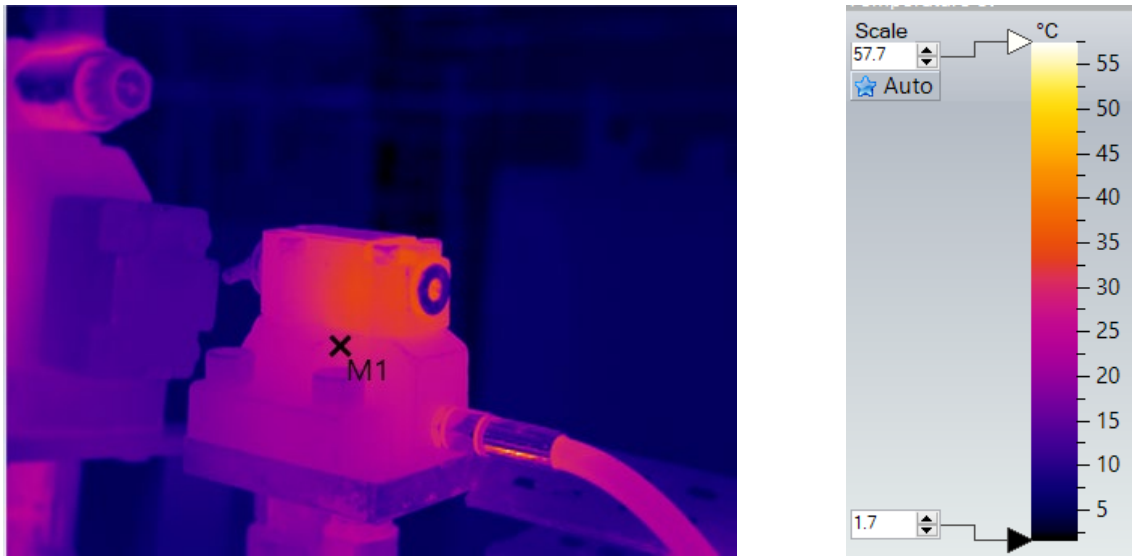


Fig. 1. *The temperatures of the pressure relief valve were recorded during the first hour of diagnostics*

From the figure, it can be concluded that the heating during the first hour of operation was relatively low and that no drastic or concerning changes occurred in the observed valve. The valve temperature was 28.1 °C at the time of recording.

After two hours of machine operation, the temperatures measured on the Bowen valve assembly exhibited variations, with the most significant temperature increase recorded on the pressure relief valve. Fig. 2 illustrates the temperatures observed after entering the second hour of machine operation

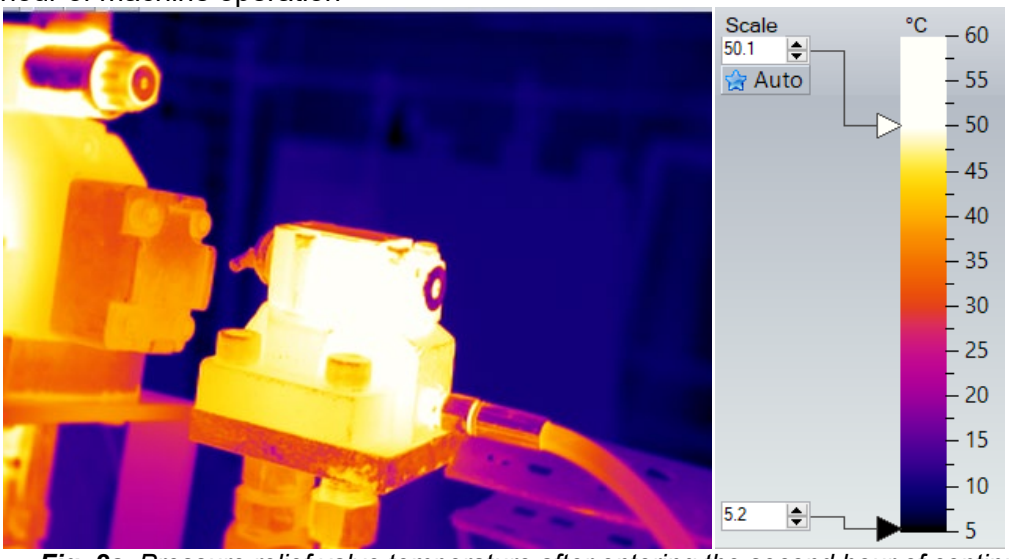


Fig. 2a. *Pressure relief valve temperature after entering the second hour of continuous machine operation*



Fig 2b. *Pressure relief valve*

From the thermal image, it can be observed that, compared to the first hour of machine operation, there has been a noticeable heating of the pressure relief valve, with the thermal image indicating that the temperature of the observed valve has now reached a value of 53.6 °C.

Towards the end of the second hour and at the onset of the third hour, critical heating was observed in the section of the machine connecting the pressure relief valve to the reservoir, as shown in Fig. 3.

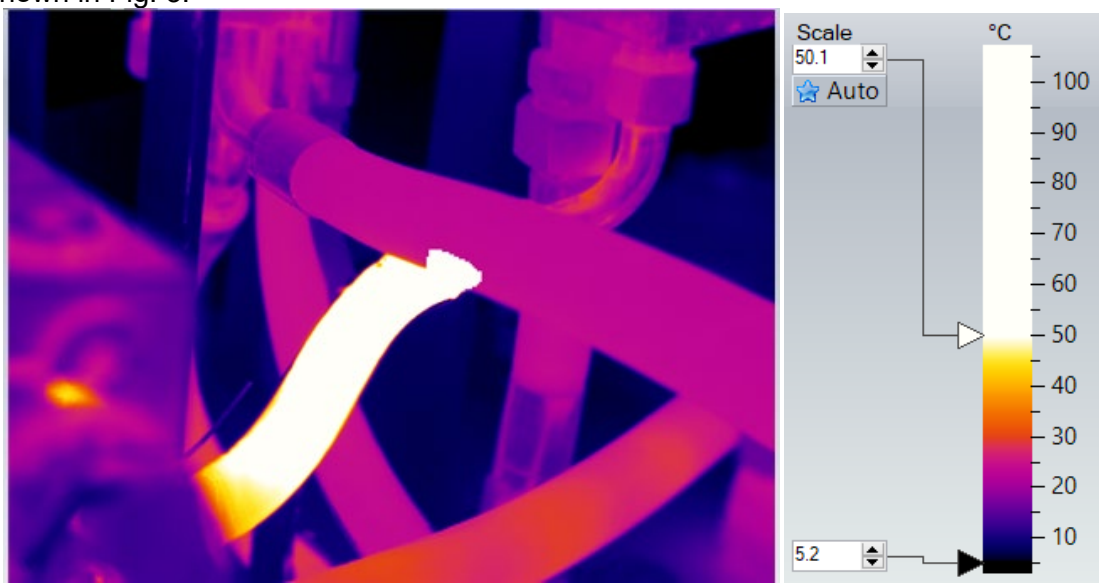


Fig. 3a. *Temperatures after two hours of machine operation on the T-line of the pressure relief valve*

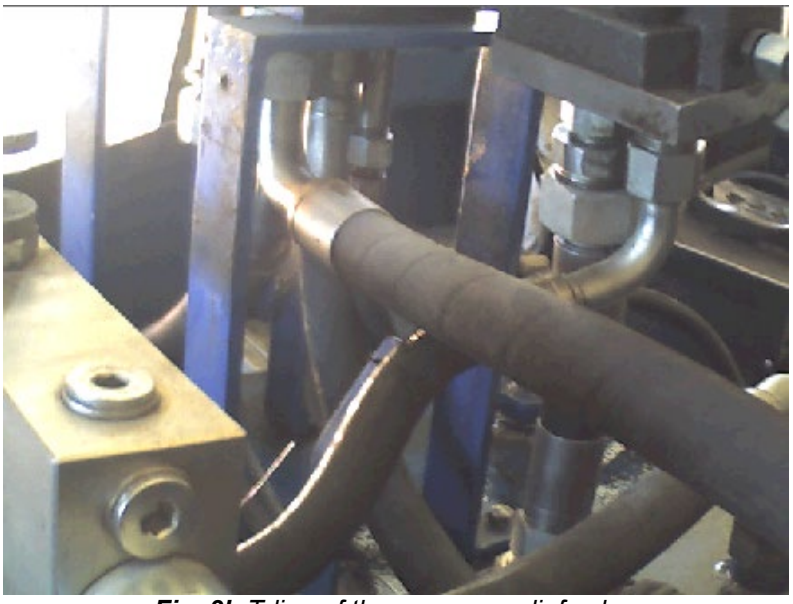


Fig. 3b. *T-line of the pressure relief valve*

After a two-hour period of machine operation, temperatures exceeding the allowable heating limits of the components, i.e., above 50 °C, were observed. The figure shows that on the T-line from the pressure relief valve to the reservoir, a temperature of 96.5 °C was recorded, representing exceptionally high temperatures for this type of system.
Fig. 4 shows the reservoir, which also began to heat up after a two-hour period of operation, with its temperature increasing exponentially. This confirms that the oil in the reservoir cannot cool down sufficiently quickly due to the malfunctioning of the valve.

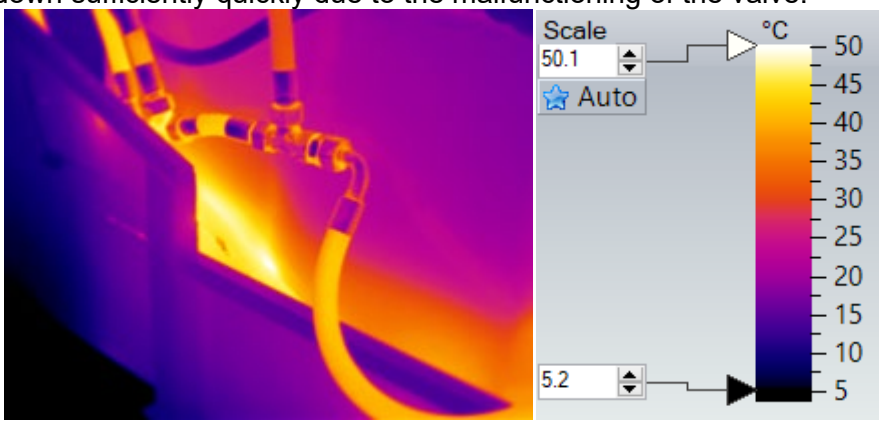


Fig. 4a. *Temperature of the hydraulic system reservoir.*



Fig 4b. *Hydraulic reservoir.*

From Fig. 4, it can be seen that the heating poses a potential risk of contamination of the hydraulic oil within the system. After two hours of operation, the oil temperature in the reservoir began to rise, reaching 46.5 °C.
Based on a three-hour monitoring of the pressure relief valve, it can be observed and concluded, from the thermal image obtained through thermographic inspection and diagnostics, that the central issue of the Bowen system is the heating generated by the pressure relief valve, which is definitively malfunctioning. A potential cause of the pressure relief valve malfunction in this system is the weakening of the valve spring, leading to frequent 'opening' of the valve, thereby preventing the oil in the reservoir from cooling properly.
The heating of hydraulic components and hydraulic oil in the system should not exceed 50 °C, as it can cause numerous issues, both technical and economic in nature. Temperatures exceeding this threshold generally lead, over time, to contamination of the hydraulic fluid, which results in the degradation of the hydraulic system, pipelines, components, valves, and the pump. Temperature must be maintained within optimal limits, and in order to thoroughly monitor it, thermography should be applied as a diagnostic method.

Table 1. *Analysis of temperature changes of hydraulic system components*

Temperature (ºC)	One hour	Two hour	Three hour
Pressure relief valve	28,1	53,6	96,5
Reservoar	22,3	40,5	46,5
Directional valve	20,2	28,9	40,5
Axial – piston pump	25,2	42,9	46,6

The temperature of the pressure relief valve exhibits a pronounced increase, rising from an initial 28.1 °C after one hour of operation to 53.6 °C in the second hour, representing a growth of approximately 90.75%. By the third hour, the temperature reaches 96.5 °C, which corresponds to a cumulative increase of about 243.42% compared to the initial value. This dynamic indicates intense operational loading of the valve and potential energy losses in the form of heat due to high flow rates and pressure drops.
The reservoir demonstrates a milder temperature rise compared to the valve, increasing from 22.3 °C to 40.5 °C after two hours (an 81.61% increase), followed by a moderate rise to 46.5 °C in the third hour, representing a total increase of approximately 108.52% from the starting value. This trend is consistent with the reservoir's function of absorbing and dissipating part of the system's thermal load.
For the directional valve, the temperature rises from 20.2 °C to 28.9 °C after the second hour (a 43.07% increase), and subsequently to 40.5 °C in the third hour, corresponding to a cumulative growth of about 100.50%. Such an increase suggests a gradual escalation of friction and internal flow losses within the valve channels during continuous operation.
The axial piston pump records a temperature rise from 25.2 °C to 42.9 °C in the second hour (a 70.24% increase), then reaching 46.6 °C in the third hour, which constitutes a cumulative increase of 84.92%. This outcome suggests stabilization of the pump's thermal regime following the initial rapid increase, likely due to a thermal balance between the heat generated and its dissipation through the working fluid.
Overall, the observed temperature trends indicate that the pressure relief valve represents the critical point in terms of thermal loading of the system, whereas the reservoir and pump are less exposed to extreme heating, yet still exhibit significant changes that may affect the viscosity of the working fluid and the overall energy efficiency.

CONCLUSION

The thermographic analysis of the Bowen HR560 coiled tubing unit has clearly demonstrated that the pressure relief valve constitutes the most critical thermal stress point within the hydraulic system. Recorded temperature progression from 28.1 °C after one hour to 96.5 °C after three hours of operation significantly exceeds the generally accepted operational

threshold of 50 °C for hydraulic components. This abnormal heating pattern is indicative of a malfunction, most likely associated with the weakening of the valve's return spring, causing frequent and unnecessary opening cycles. Such behavior not only prevents the hydraulic oil in the reservoir from cooling effectively but also accelerates fluid degradation, promotes contamination, and increases the likelihood of premature wear of other hydraulic components.

The operational integrity of the pressure relief valve is paramount, as it governs the system's maximum operating pressure, protects downstream components from overload, and ensures the safe and efficient performance of the entire hydraulic assembly. Its malfunction compromises the stability of the hydraulic circuit, introduces additional thermal and mechanical loads, and reduces overall system reliability. Moreover, elevated oil temperatures detrimentally affect viscosity, film strength, and lubrication quality, further contributing to the deterioration of pumps, directional valves, and associated pipelines.

Infrared thermography, applied as a non-invasive diagnostic method, has proven to be a highly effective tool for detecting early-stage anomalies under real operating conditions without interrupting the operational cycle. Its ability to identify localized overheating enables targeted maintenance interventions before minor defects escalate into costly and potentially hazardous failures. When integrated with conventional hydraulic monitoring parameters such as pressure and flow rate, thermography supports predictive maintenance strategies, extends component lifespan, and improves operational safety.Given the critical nature of the observed overheating in the pressure relief valve, it is recommended to implement regular thermographic inspections as part of the maintenance routine, alongside thorough mechanical checks and calibration of pressure control components. This approach not only safeguards the reliability and safety of coiled tubing units in demanding oilfield applications but also contributes to optimizing energy efficiency, minimizing unplanned downtime, and ensuring long-term operational sustainability of complex hydraulic systems.

REFERENCES

[1] Zhao, R., Yan, R., Chen, Z., Mao, K., Wang, P., Gao, R. X.,Deep learning and its applications to machine health monitoring. Mechanical Systems and Signal Processing, 115, pp. 213-237, 2019.

[2] Carvalho, T. P., Soares, F. A., Vita, R., Francisco, R. D. P., Basto, J. P.,Alcalá, S. G., A systematic literature review of machine learning methods applied to predictive maintenance. Computers & Industrial Engineering, 137, 106024, 2019.

[3] Lei, Y., Li, N., Guo, L., Li, N., Yan, T., Lin, J., Machinery health prognostics: A systematic review from data acquisition to RUL prediction. Mechanical systems and signal processing, 104, 799-834, 2018.

[4] Behnia, F., Ahmadabadi, H. Z., Schuelke-Leech, B. A.,Mirhassani, M., Developing a fuzzy optimized model for selecting a maintenance strategy in the paper industry: An integrated FGP-ANP-FMEA approach. Expert Systems with Applications, 232, 120899, 2023.

[5] Netsch, C., Schöpe, T., Schindele, B., Jayakumar, J.,DeepFMEA--A Scalable Framework Harmonizing Process Expertise and Data-Driven PHM. arXiv preprint arXiv:2405.08041, 2024.

[6] Theissler, A., Pérez-Velázquez, J., Kettelgerdes, M.,Elger, G.,Predictive maintenance enabled by machine learning: Use cases and challenges in the automotive industry. Reliability engineering & system safety, 215, 107864, 2021.

[7] Qiu, S., Cui, X., Ping, Z., Shan, N., Li, Z., Bao, X., Xu, X., Deep learning techniques in intelligent fault diagnosis and prognosis for industrial systems: A review. Sensors, 23(3), 1305, 2023.

[8] Martínez-Heredia, A. M., Ventura, S., Weak Supervision: A Survey on Predictive Maintenance. Wiley Interdisciplinary Reviews: Data Mining and Knowledge Discovery, 15(2), e70022, 2025.

[9] Ucar, A., Karakose, M., Kırımça, N., Artificial intelligence for predictive maintenance applications: key components, trustworthiness, and future trends. Applied Sciences, 14(2), 898, 2024.
[10] Venegas, P., Ivorra, E., Ortega, M.,Sáez de Ocáriz, I., Towards the automation of infrared thermography inspections for industrial maintenance applications. Sensors, 22(2), 613, 2022.
[11] Qureshi, U. R., Rashid, A., Altini, N., Bevilacqua, V., La Scala, M., Radiometric infrared thermography of solar photovoltaic systems: An explainable predictive maintenance approach for remote aerial diagnostic monitoring. Smart Cities, 7(3), pp.1261-1288, 2024.
[12] Wu, X., Zhou, B., Lin, P., Cao, R., Huang, F., Infrared polarization imaging-based non-destructive thermography inspection. arXiv preprint arXiv:2405.03126, 2024.
[13] Hellemans, M., The safety relief valve handbook: Design and use of process safety valves to ASME and International Codes and Standards. Elsevier, 2009.
[14] Zappe, R. W., Valve selection handbook. Gulf Professional Publishing, 1999.
[15] Bhowmik, P. K.,Sabharwall, P., Sizing and Selection of Pressure Relief Valves for High-Pressure Thermal–Hydraulic Systems. Processes, 12(1), 21, 2023.
[16] Novaković, B. Z., Djordjević, L., Đurđev, M., Radovanović, L., Zuber, N., Desnica, E., Bakator, M., Effect of changes in hydraulic parameters and tank capacity of the hydraulic press system on the heating of the hydraulic oil, Maintenance & Reliability/EksploatacjaiNiezawodność, 26(4), 2024.

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ENHANCING DECISION SUPPORT SYSTEMS THROUGH AI-DRIVEN ADAPTIVE WEIGHTING METHODS

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Abstract: This paper presents an interactive-simulational framework for improving the determination of weighting coefficients in Analytic Hierarchy Process (AHP)-based multi-criteria decision-making. By integrating Monte Carlo simulation with Random Forest regression, the proposed method models uncertainty in user preferences and generates robust, personalized weight predictions without relying on extensive historical data. Experimental results on a case study with three criteria demonstrate that the approach preserves core priority structures while enhancing prediction stability and accuracy. The framework offers a flexible and adaptive solution suitable for AI-supported decision support systems, contributing to more reliable and transparent decision-making processes. Future research will explore expanded criteria and alternative machine learning techniques to further improve model performance.
Key words: AI-based decision support systems (AI-DSS); artificial intelligence (AI); decision support systems (DSS); Random Forest Regression.

INTRODUCTION

The Analytic Hierarchy Process (AHP) method belongs to the family of multi-criteria decision-making models with preference weighting (MCDM). The most frequently criticized aspect of this method in professional and scientific literature concerns the subjectivity involved in prioritizing criteria, specifically the assignment of weighting coefficients by the decision-maker, which is often cited as its greatest drawback. However, in individual decision-making situations, this characteristic can be seen as an advantage, as it allows customization of decisions according to the personal preferences of the decision-maker [1, 2, 3]. In the context of group decision-making or consensus building, generating weighting coefficients becomes a challenge and has been the subject of numerous studies. In response to this challenge, various modifications of the AHP method have been developed, such as fuzzy AHP, and others. This research examines the application of different artificial intelligence (AI) models in the automated generation of weighting coefficients and verification of results against expert assessments.

To overcome subjectivity in assigning weights within the AHP method, contemporary research increasingly explores the use of various AI models. One approach involves artificial neural networks (ANN), which, based on historical decision-making data, can learn prioritization patterns and independently generate weights, additionally, phase-AHP represents a significant modification of classical AHP by allowing the introduction of fuzzy and indeterminate values during the evaluation process, thus more adequately modeling uncertainty in the decision-maker's preferences [3, 4]. Within optimization techniques, genetic algorithms (GA) are used to search the space of possible weight configurations to determine the optimal combination satisfying defined efficiency and consistency criteria [5, 6].

Recent studies also explore the application of decision tree algorithms and techniques such as Random Forest, which can objectively assess the relative importance of criteria based on their frequency and significance in the past. With the development of deep learning, particularly through LSTM and transformer models, new opportunities arise for implementing advanced structures in multi-criteria decision-making, especially in systems involving temporal or textual decision dimensions. In the study by Heinrich et al. [7], three archetypes of AI-based decision support systems (AI DSS) are examined: systems based on generative models, explainable AI systems, and traditional machine learning algorithms without interpretability. The research aimed to determine how different user profiles evaluate the key characteristics of these systems in the context of high-risk industrial forecasting. The authors applied the Analytic

Hierarchy Process (AHP) method to quantify the relative importance of three decision criteria: system performance, implementation effort, and transparency. Participants (N = 69) performed pairwise comparisons among criteria and DSS archetypes, and the obtained weighting coefficients were analyzed according to user expertise level. Results showed that users in such contexts value system performance the most (with an average priority value of 0.47), while transparency was considered the least important (0.23), especially among more experienced users. Conversely, less experienced users exhibited a greater preference for transparent solutions. The study indicates statistically significant differences in preferences between different user groups, confirming the need for adaptive AI DSS systems that enable dynamic personalization of weighting coefficients based on user profiles. The findings provide empirical support for the use of the AHP method in automated weight generation within intelligent decision support systems.

In contemporary scientific and professional literature, the application of artificial intelligence (AI) in decision support systems (DSS) shows significant growth and diversity across various fields and industries. The work of Deliu and Chakraborty [8] highlights specific applications of AI-DSS in the field of precision and digital medicine, emphasizing how these technologies enable personalized and more efficient medical decisions. Similarly, Kose et al. [9] examine deep learning as a fundamental approach in medical DSS, providing a foundation for the development of intelligent systems in healthcare.

In the area of sustainable business, authors of research [10] emphasize the role of AI-DSS in supporting the circular economy, pointing to the potential of these systems to contribute to ecologically and economically sustainable decisions through resource and process optimization. This broader thematic perspective is further developed in the book [11], which presents a comprehensive overview of the latest advances in AI-powered DSS, including applications in medicine, urban studies, and industry, as well as the development of new decision-making methodologies.

The review [12] focuses on Industry 4.0, analyzing how AI integrates and enhances DSS through machine learning, deep learning, and natural language processing with the aim of improving supply chain management, predictive maintenance, and energy efficiency. A similar multidisciplinary approach is taken by Gupta et al. [13], who investigate the contribution of AI in operations research, emphasizing the necessity of synergy between theoretical models and practical applications in complex and uncertain environments.

A special place is held by the study of Kostopoulos et al. [14], who address the challenges and techniques of explainable artificial intelligence (XAI) in DSS, stressing the importance of transparency and interpretability of models to increase user trust and the quality of decision-making. This dimension of trust and ethics is further emphasized in the work of Kovari [15], who analyzes how accuracy and transparency are balanced in AI-DSS across various industries, highlighting key factors that influence the adoption and effectiveness of these systems.

Review studies clearly highlight the timeliness and growing importance of AI-powered decision support systems across different fields and point to the need for further research, particularly in areas of explainability, ethics, and user acceptance, to ensure broad and sustainable application of AI technologies in decision-making processes.

METHODOLOGY

In situations where historical evaluations of decision-maker (DM) preferences are lacking, this study proposes an interactive-simulational framework in which a Random Forest algorithm is trained on generated preferences derived from expert scripts and user responses to targeted preferential questions.

The choice of an appropriate machine learning model for predicting weighting coefficients within multi-criteria decision-making depends on several factors, including data complexity, dataset size, interpretability requirements, and noise robustness. Random Forest is often a suitable choice due to its robustness, ability to model nonlinear relationships, and resistance to overfitting. This model aggregates results from a large number of decision trees, enabling it

to capture complex patterns in the data while providing relatively good interpretability through feature importance analysis.
However, depending on the problem specifics, other models such as Gradient Boosting Machines (e.g., XGBoost, LightGBM) may offer higher accuracy, especially on large and complex datasets, albeit at the cost of more careful hyperparameter tuning and less interpretability. Linear regression models or regularized approaches (Lasso, Ridge) may be more appropriate when transparency and simplicity are prioritized, though their ability to capture complex nonlinear relationships is limited. For small to medium-sized datasets, such as the simulated set considered here, Random Forest strikes a balance between performance and implementation simplicity. Its robustness to noise and ability to estimate prediction variability also make it well-suited for modeling variations arising from Monte Carlo simulation of user weights.
The thus constructed interactive-simulational framework enables prediction of weighting coefficients without relying on prior empirical data, thereby facilitating the generation and application of AHP models in contexts with limited experiential inputs. The proposed framework consists of four interrelated phases: interactive input of user preferences through pairwise comparisons, Monte Carlo simulation generating a set of realistic variations of weight vectors, training a Random Forest model on these simulated data, and finally generating precise and robust AHP matrices for decision-making purposes.
The experimental research plan through these four phases was realized as follows: after the user inputs their preferences via pairwise comparisons of criteria using Saaty's scale, the initial weighting vector is calculated by applying the standard AHP algorithm. However, to mitigate the potential subjectivity and variability in user assessments, the proposed framework incorporates an additional processing layer in the form of Monte Carlo simulation. This simulation generates a large number of weight vector variants based on the input preferences, maintaining the basic priority structure while introducing controlled noise to model realistic deviations in perceived criterion importance. The resulting set of simulated vectors is then used to train the Random Forest model, where the original user preferences serve as input variables and the corresponding weight variations as output target values. In this way, the developed model learns the patterns of relationships between user assessments and weight distributions, enabling prediction of stable and personalized weighting vectors for new users or similar decision-making contexts. Such a multilayer approach ensures greater robustness, resistance to extreme inputs, and a higher degree of adaptation to the decision-maker's profile, significantly improving the quality and reliability of multi-criteria evaluations within AI-supported decision support systems.
In practice, the proposed framework is intended to be integrated into an intelligent decision support system (AI DSS) via a simple and guided user interface, enabling its use by decision-makers without prior knowledge of multi-criteria methods or machine learning. In the initial phase, the user is asked a limited number of carefully designed preferential questions aimed at identifying their core value orientations regarding key decision criteria. Based on the provided responses and the specific problem context, the embedded Random Forest model, trained on simulated and structured data, automatically generates the corresponding weighting coefficients. The obtained values are then integrated into the AHP pairwise comparison matrix, which is used to rank available alternatives. The decision-maker is offered visual validation of the proposed weights and, if necessary, manual adjustment options with a display of the effects such changes may have on the final decision. In this manner, the system provides personalized, transparent, and methodologically sound decision-making even in conditions of limited empirical data, significantly enhancing the accessibility and flexibility of multi-criteria models across diverse domain-specific decision contexts.

EXPERIMENTAL STUDY

For the purpose of testing the methodological steps of the proposed interactive-simulational framework, a Python codebase was developed in this study utilizing modern libraries for data processing and machine learning, including pandas and numpy for data management, scikit-

learn for implementing the Random Forest algorithm, and random for generating synthetic variations. The implementation is structured to cover all key phases of the methodology: interactive input of user preferences through pairwise comparisons of criteria based on Saaty's scale, calculation of the initial AHP weighting vector, followed by Monte Carlo simulation generating a large number of realistic variants of this vector, and finally training the Random Forest model on the simulated data. The resulting trained model enables prediction of stable and personalized weighting coefficients for new users, based on patterns observed in the simulated variations, thereby providing flexible and adaptive support for multi-criteria decision-making. In this manner, the developed code enables experimental verification of the proposed framework's ability to automatically generate AHP weights without requiring prior empirical evaluations, and forms the basis for its application within AI-supported decision support systems (DSS).

Within the experimental application of the developed model, testing was conducted on a single case study involving three criteria: performance, cost, and transparency. The user provided pairwise comparisons using Saaty's scale, rating performance as significantly more important than cost (value 7), moderately more important than transparency (value 3), and cost as substantially more important than transparency (value 5). Based on these inputs, the initial weighting vector calculated using the AHP method indicated that the performance criterion holds a dominant weight of 0.6215, followed by cost with a weight of 0.2581, and transparency with the smallest weight of 0.1204. Figure 1 illustrates an example of the interaction with the decision-maker aimed at generating the initial weighting vector.

```
print("\nResults saved to 'initial_ahp_weights.csv' and 'final_predicted_weights.csv'.")
```

```
Please compare the following pairs of criteria using Saaty's scale:
1 = equal importance, 3 = moderate, 5 = strong, 7 = very strong, 9 = extreme
Use reciprocals (e.g., 1/3) if the second criterion is more important.

How much more important is PERFORMANCE compared to COST? 7
```

Fig. 1. *Interactive entry of the initial vector of weighting coefficients*

After the decision-maker provides ratings through pairwise comparisons of criteria based on Saaty's scale, the initial user profile is transformed into a set of input features representing preferences in the form of discrete indicators. These input values serve as the primary data for training the Random Forest model. Subsequently, Monte Carlo simulation is employed to generate a large number of variations of the weighting coefficient vectors (Figure 2), which model potential deviations and uncertainties inherent in the user assessments. The generated variations constitute the target values, i.e., the output data to which the model adapts during the learning process.

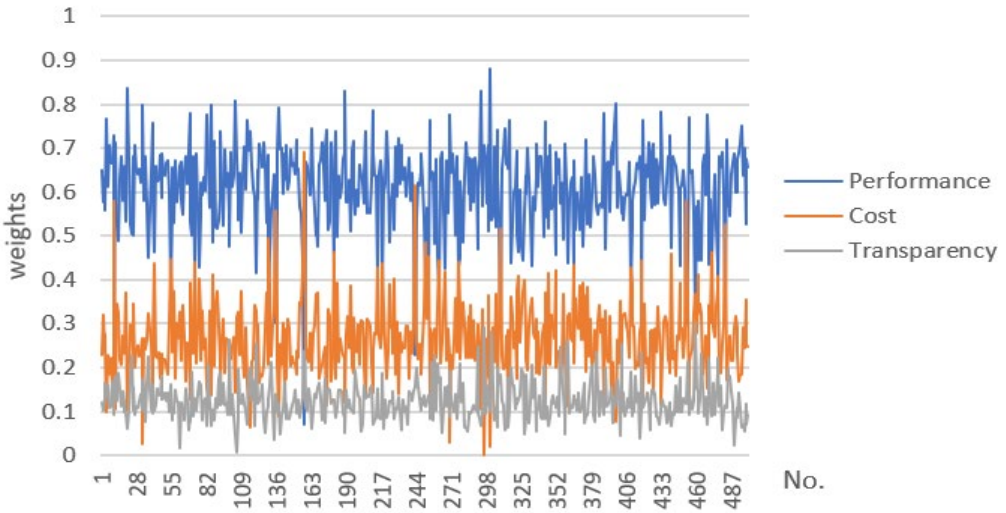


Fig. 2. *Monte Carlo weigths simulation results*

During the training phase, the Random Forest learns the relationships between user preferences and realistic distributions of weighting coefficients. A separate regression model is built for each criterion to predict its corresponding weight. This approach enables the model to generalize from the available simulated data and to generate stable and reliable weight predictions when new user inputs arise.
This methodology contributes to improving the accuracy and relevance of multi-criteria evaluations within artificial intelligence-based decision support systems.

```
# 9. SAVE RESULTS
pd.DataFrame([user_weights_dict]).to_csv("initial_ahp_weights.csv", index=False)
pd.DataFrame([final_weights]).to_csv("final_predicted_weights.csv", index=False)
print("\nInitial and final weights saved to CSV files.")
```

```
Please compare the following pairs of criteria using Saaty's scale:
1 = equal importance, 3 = moderate, 5 = strong, 7 = very strong, 9 = extreme
Use reciprocals (e.g., 1/3) if the second criterion is more important.

How much more important is PERFORMANCE compared to COST?  7
How much more important is PERFORMANCE compared to TRANSPARENCY?  3
How much more important is COST compared to TRANSPARENCY?  5

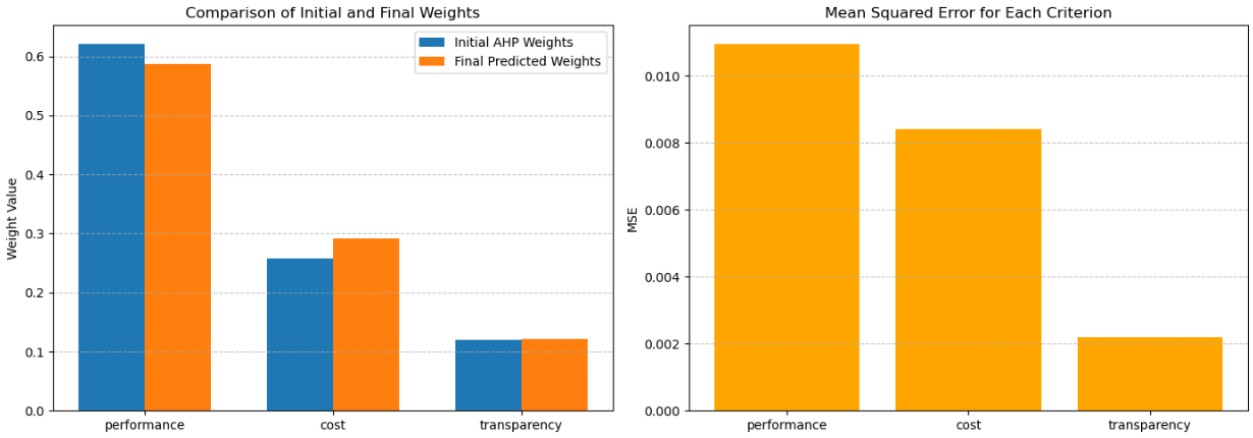
Initial AHP-derived weights:
performance: 0.6215
cost: 0.2581
transparency: 0.1204
Monte Carlo simulation set saved to 'monte_carlo_simulation_set.csv'
MSE for performance: 0.010959
MSE for cost: 0.008420
MSE for transparency: 0.002188

Final predicted weights by Random Forest:
performance: 0.5876
cost: 0.2915
transparency: 0.1208

Initial and final weights saved to CSV files.
```

Fig. 3. *Testing model of case study*

By employing a combined approach that integrates Monte Carlo simulation and Random Forest regression, the final predictions of weighting coefficients were obtained, which slightly deviate from the initial values derived by the AHP method: performance was estimated at 0.5876, cost at 0.2915, and transparency at 0.1208 (see Fig. 3). These results confirm that the model successfully preserves the core structure of user priorities, while simultaneously enabling a more robust and adapted estimation of weights that mitigates the effects of uncertainty and potential errors in assessments. Such characteristics of the model suggest its applicability in real-world decision-making scenarios, where precise and reliable determination of criterion weights is crucial.
To evaluate the model's accuracy, the mean squared error (MSE) was calculated for each criterion on the test dataset used for evaluating the Random Forest model after a 70/30 data split. The MSE values are moderate, with 0.010959 for performance, 0.008420 for cost, and 0.002188 for transparency, indicating a good level of prediction accuracy, but also some variability in results compared to previous experiments.



a) b)

Fig. 4. *MSE by criteria*

Figure 4a presents a comparison between the initial weighting coefficients obtained through the direct application of the AHP method on the user's pairwise preferences and the final weights predicted using the Random Forest model after a Monte Carlo simulation with an increased noise level. The chart clearly shows that the criterion "performance" dominates with a weight of approximately 0.62, reflecting a strong priority assigned by the user to efficiency or solution quality. The next most significant criterion is "cost," with a weight around 0.29, while "transparency" holds the lowest weight of approximately 0.12. It is notable that the final predicted weights slightly differ from the initial ones, indicating that the model introduces certain adjustments that contribute to increased robustness and stability of the weight estimations, while maintaining the fundamental preference patterns of the user.

Figure 4b displays the mean squared errors (MSE) of the model for each criterion, representing the average squared difference between the actual simulated and predicted weighting coefficients on the test dataset. The criterion "performance" exhibits the highest MSE value of about 0.011, indicating increased variability in predictions compared to earlier results, yet still demonstrating an acceptable level of accuracy. The MSE values for "cost" and "transparency" are lower, approximately 0.008 and 0.002 respectively, indicating solid accuracy of the model in predicting weights for these criteria. These values confirm that the model maintains good predictive capability even with the introduction of greater uncertainty through simulation.

CONCLUSION

This study addressed the challenges of subjectivity and uncertainty in determining weighting coefficients within the Analytic Hierarchy Process (AHP) for multi-criteria decision-making. Recognizing the limitations of traditional approaches that largely rely on expert judgment and static input preferences, an interactive-simulational framework integrating Monte Carlo simulation and Random Forest regression was proposed. This hybrid approach enables the generation of realistic variations in weighting vectors that reflect potential user uncertainty and facilitates the training of robust predictive models capable of adapting to new decision-makers' preferences.

The experimental evaluation conducted on a representative case study involving performance, cost, and transparency criteria demonstrated that the proposed model successfully preserves the core structure of user priorities while enhancing the robustness and stability of weight predictions. The achieved prediction accuracy, confirmed by moderate mean squared error values, indicates the model's effectiveness in managing the uncertainty inherent in user assessments.

Furthermore, the framework's adaptability and its capacity for personalized weighting underscore its practical applicability in real-world decision support systems, especially in contexts with limited historical data. By providing a flexible, transparent, and methodologically

sound mechanism for weight determination, the proposed approach contributes to improving the quality and reliability of AI-supported multi-criteria evaluations.
Future work may focus on extending the methodology by including additional criteria, exploring alternative machine learning models, and validating the approach across various application domains to further enhance decision-making efficiency.

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REFERENCES

[1] Köksalan, M., Wallenius, J., & Zionts, S. (2011). Multiple Criteria Decision Making: From Early History to the 21st Century. Springer. https://doi.org/10.1142/8042
[2] Vaidya, O. S., & Kumar, S. (2006). Analytic hierarchy process: An overview of applications. European Journal of Operational Research, 169(1), 1–29. https://doi.org/10.1016/j.ejor.2004.04.028
[3] Saaty, T. L., & Vargas, L. G. (2006). Decision making with the analytic network process: Economic, political, social and technological applications with benefits, opportunities, costs and risks. Springer. https://doi.org/10.1007/978-1-4614-7279-7
[4] Kahraman, C., Cebeci, U., & Ulukan, Z. (2003). Multi-criteria supplier selection using fuzzy AHP. Logistics Information Management, 16(6), 382–394. https://doi.org/10.1108/09576050310503367
[5] Wang, Y.M., & Elhag, T. M. S. (2006). Fuzzy TOPSIS method based on alpha level sets with an application to bridge risk assessment. Expert Systems with Applications, 31(2), 309–319. https://doi.org/10.1016/j.eswa.2005.09.040
[6] Moussaoui, F., Cherrared, M., Kacimi, M. A., & Belarbi, R. (2018). A genetic algorithm to optimize consistency ratio in AHP method for energy performance assessment of residential buildings: Application of top-down and bottom-up approaches in Algerian case study. Sustainable Cities and Society, 42, 622–636. https://doi.org/10.1016/j.scs.2017.08.008
[7] Heinrich K, Janiesch C, Krancher O, Stahmann P, Wanner J, Zschech P (2025) Decision factors for the selection of AI-based decision support systems—The case of task delegation in prognostics. PLoS One 20(7): e0328411. https://doi.org/10.1371/journal.pone.0328411
[8] Deliu, N., & Chakraborty, B. (2023). Artificial Intelligence-based Decision Support Systems for Precision and Digital Health. Electronics, 13(14), 2842.
[9] Kose, U., Deperlioglu, O., Alzubi, J., & Patrut, B. (2020). Deep learning for medical decision support systems (pp. 1–14). Springer Singapore. https://doi.org/10.1007/978-981-15-6325-6_1
[10] Deveci, M., Delen, D., & Ding, W. (2024). AI-based decision support systems for sustainable business management under circular economy: Preface. Annals of Operations Research, 342, 1–3. https://doi.org/10.1007/s10479-024-06347-0
[11] Tsihrintzis, G. A., Virvou, M., Doukas, H., & Jain, L. C. (Eds.). (2024). Advances in Artificial Intelligence-Empowered Decision Support Systems: Papers in Honour of Professor John Psarras. Springer Nature. https://doi.org/10.1007/978-3-031-62316-5
[12] Soori, M., Ghaleh Jough, F. K., Dastres, R., & Arezoo, B. (2024). AI-based decision support systems in Industry 4.0: A review. Journal of Economy and Technology. Advance online publication. https://doi.org/10.1016/j.ject.2024.08.005
[13] Gupta, S., Modgil, S., Bhattacharyya, S., & Bose, I. (2022). Artificial intelligence for decision support systems in the field of operations research: Review and future scope of research. Annals of Operations Research. Advance online publication. https://doi.org/10.1007/s10479-020-03856-6

[14] Kostopoulos, G., Davrazos, G., & Kotsiantis, S. (2024). Explainable artificial intelligence-based decision support systems: A recent review. Electronics, 13(14), 2842. https://doi.org/10.3390/electronics13142842
[15] Kovari, A. (2024). AI for decision support: Balancing accuracy, transparency, and trust across sectors. Information, 15(11), 725. https://doi.org/10.3390/info15110725

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KINDS OF SHRINKAGE DURING MELTING AND SOLIDIFICATION OF A METAL

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Abstract: Shrinkage is a pretty important property after the metal is being melted and solidificated, for obtaining the desired dimension(s) of the projected castings. Shrinkage is just an oposite physical property to the elongation, i.e. dilataion. For all known metals from the nature or used in the technique, the dilatation or shrinkage properties could not be considered as one constant value from the crystallization periode troughout the solid state, it means up to the room temperature. If the metal/alloy shows the phase transition phenomenon than the problem of representing those values by one number may becomes more complex, even unsusstainable.
On the shrinking behavior during solidification of a metal, as in casting, a lot of factors may have affect, pretty more than at laboratory conditions. Such changes in dimensions are of importance for almost products made by using different technologies, as welding or brazing.

Key words: dilatation, shrinkage, melting, solidification, porosity

INTRODUCTION

It is a habit that dilatation or shrinkage are determined just at an temperature interval, begining from the room temperature up to the desired temperature, if is needed near to the melting [1-5]. In special cases the negative temperatures, i.e. to -80^{0}C, even lower should be is applied. In such pretty wide temperature interval sometimes is needed to diversify the kinds of shrinkage, it means after melting, just in the periode of solidification, i.e. crystallization and down to the room temperature.
Dilatation/elongation or contraction are the fundamental physical properties when any metal is undergoing to heating or cooling. In fact, contraction is just the oposite property to thermal expansion. The dilatation is expressed as function of temperature, multiplied by linear coefficient (α_t). However, the dilatation or contraction always is a volumetric property, but for the simplicity is rather expressed as one value, known as a linear expansion or dilatation. Shrinkage in casting technology shows more complex property than pure dilatation, because during solidification of molten metal inside the narrow cavity into the pattern, the great influence may have the surface tension(s). As a measure for the surface tension or wettability, commonly is used an angle between drop of the molten metal and the solid wall. So, this angle gives an explanation for good or poor fullfilling the thin walls at castings. The value of surface tension of a metal depends both from the kind of molten metal and mold material. All of those properties affect on a castability, it means for obtaining the proper dimensions and without casting deffects, either at surface or inside the wall.
Its clear that the geometrical dimensions of a body may alter when the temperature is changing. Every change in dimensions may be effectively registered at diagram dilatation - temperature.
The achieved temperature in a particular technological or melting process, may have an important influence on the value of shrinkage. Laser beams are able to heat even melt the impingnedsurface very fast, sometimes the second is a large value. Such laser characteristics find out application in industry for metal heating and melting, including brazing or welding. After reaching the desired temperature follows the cooling periode, when in many materials may be expected a (little) changes in dimensions. From that point of view is needed to know how the

used material is expanded (elongated) or shortened (shrinked). Also, the study of shrinkage and forming the residual stresses always are an important field both in engineering and science.

MATERIAL AND METHODS

1. Dilatation and shrinkage as a physical phenomenon

Dilatation or shrinkage are natural phenomenon, when variations in dimensions are measured during heating or cooling of the specimen. Any phase transformation, generally, leads to the change of crystal lattice type or parameters, which implies on change of other physical and other properties [5-7]. In the metallurgical practice it is happened during melting, solidification and in heat-treating processes (quenching and tempering), including the dissolution or precipitation of a new phase.
The variation of dimensions in fact always are volumetric, but measuring is usually provided in one direction – in length. At this measurement is recorded the (linear) displacement as u function of temperature. Such changes are measured by using an instrument based on mechanical, electrical, magnetic and/or optical principle, which are pretty well explained in broad physical or metallurgical text or handbooks [1-4]. The simpliest example of one thermal dilatation curve for pure iron is given in Fig. 1a), while the values of thermal dilatation for principal structures in steel (also in function of temperature) is given in Fig. 1b).

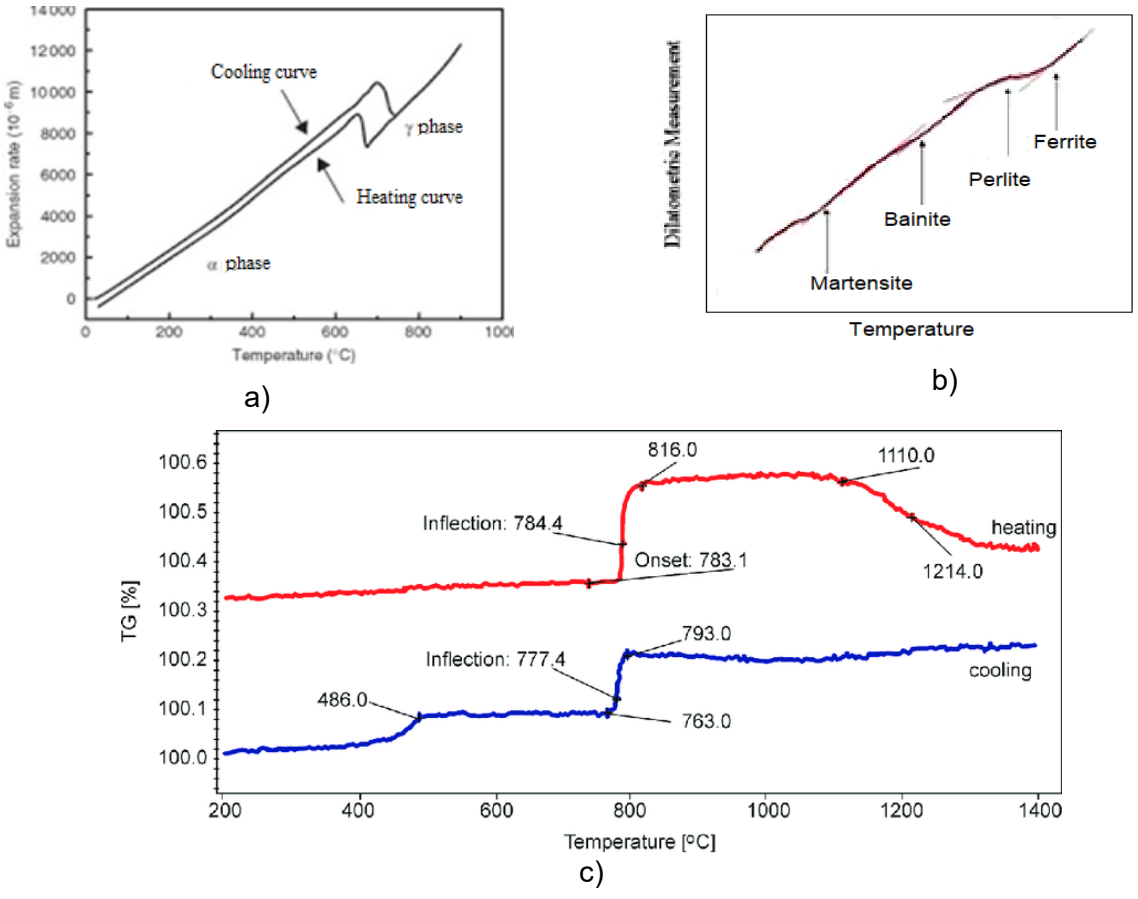


Fig. 1. *Dilatometry curves for pure iron during heating and cooling a), dilatometric values for principal structures at one common steel b) and thermomagnetometry curves for one tool steel c)*

More complex dilatation curves either durin heating or cooling may be found in medium or high alloyed steels, one example for cold work tool steel is given in Fig. 1c), obtained by

thermomagnetometry. This tool steel [8] belongs to the group of ledeburitic structure, which contains (in wt%): 2,47%C; 4,18%Cr; 3,82%Mo: 8,94%V; 1,13%W and 2,02%Co.
The obtained diagrams may serve for furter analysing the phase transformations, as dissolving carbides into matrix or for other processes during solidification, etc.
At one-phase region from Fig. 1a), the temperature influence on dimensional change could be explained by an nearly linear equation, but not at multialloyed steel, see Fig. 1c).
One specific behavior could be found at magnetic materials, when the temperature is constant but geometry of such body may be changed, in small scale, if they are exposed to the magnetic field.

2. Shrinkage effects during casting

After the liquid metal is poured into the mold cavity, Fig. 2a), shrinkage starts an idealized case [8] equaly at all sides as in Fig 2b). In reality, melted metal at a mold solidifies as in Fig. 2c), with unavoidable casting cavities, two examples of them are shown at same figure.

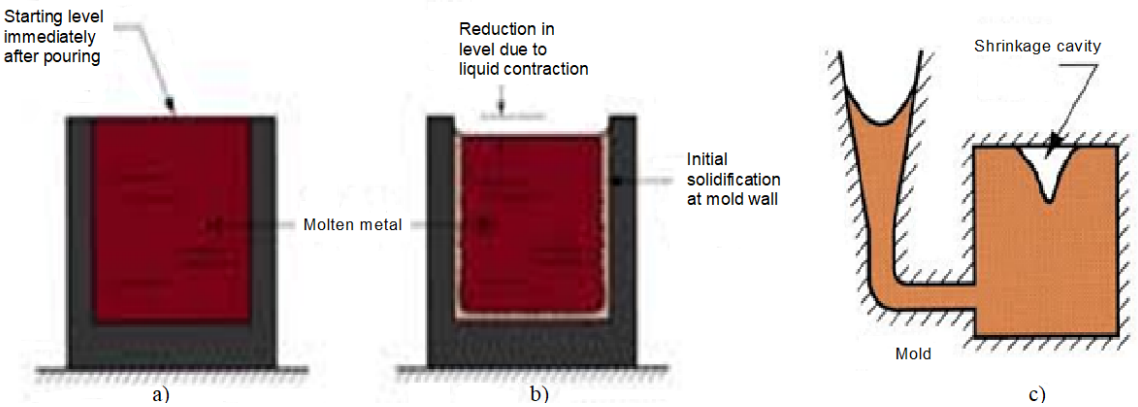


Fig. 2. *Mold cavity fullfilled with molten metal a), shrink begins when temperature is decreasing and solidification starts b) and two common shrinkage cavities formed at one simple castings with its pouring system c)*

In fact, heated metal always shrinks when the temperature is decreasing, see diagram from Fig. 3a). Crystal grains (in dendritic form) growing at an oposite direction from the heat flow, Fig. 3b), in the center of castings wall the shrinkage cavity begins to forms.

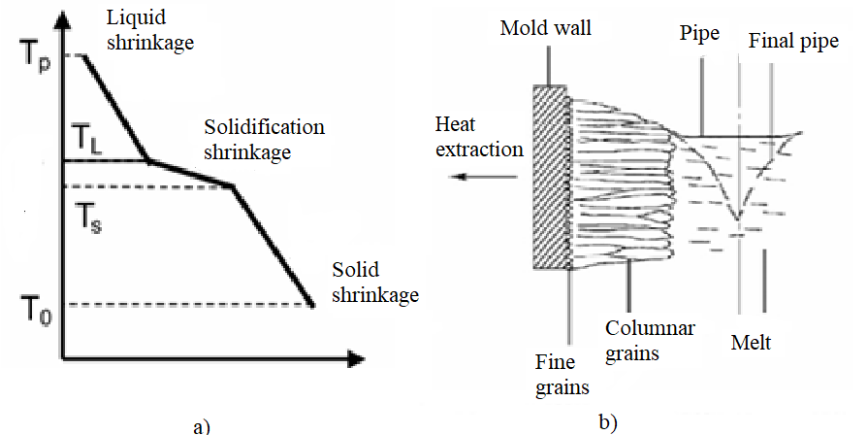


Fig. 3. *Diagram of temperature change in time a) and solidification starts with cavity forming b)*

Between solidified grains may be appeared the shrinkage cavity, Fig. 4a). After solidification is finished, few different types of shrinkage cavities may be formed, Fig. 4b). Other examples of cavities/porosities and distribution of crystal grains and some of the important details after solidification of an angot are shown in Fig. 4c).

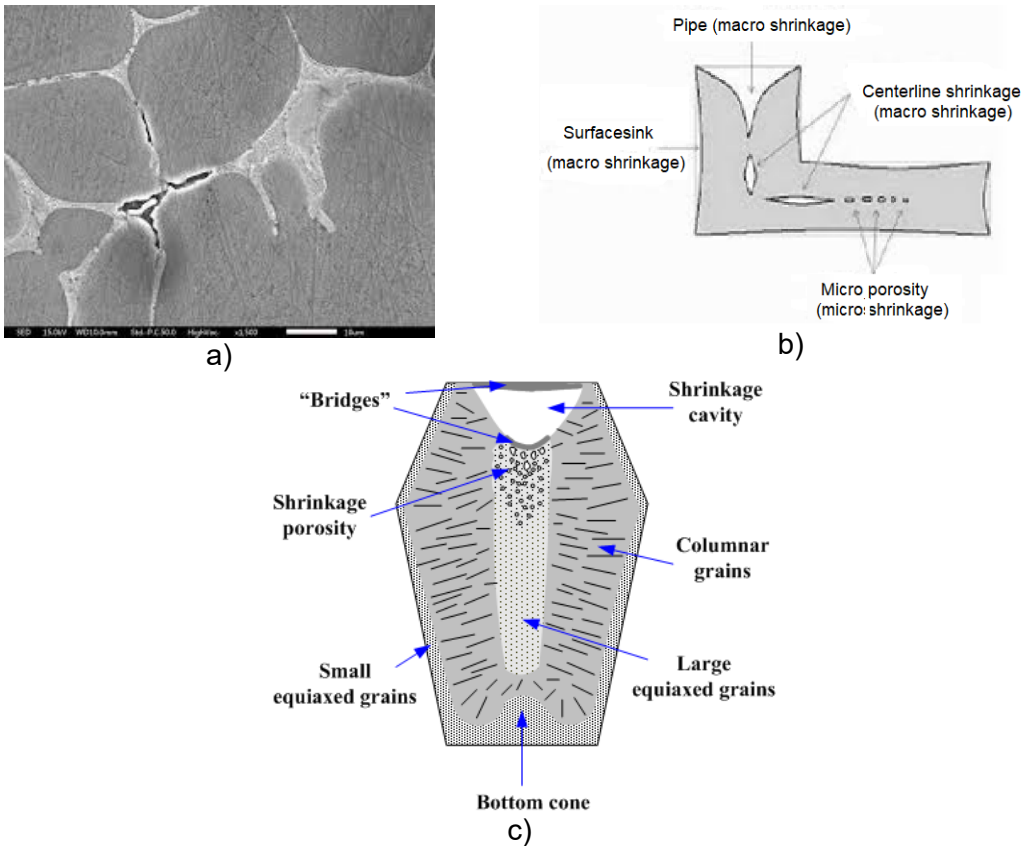


Fig. 4. *Shrinkage microcavities between solidified grains a), one part of casting with possible types of shrinkages after solidification process is finished b) and cavities and different grains at ingot c)*

As well known, the most metals shrink when cooled from the liquid state, while some of them are expanded as suggest data from Table 1.

Table 1. *Shrinkage of selected metals, their crystal structures and melting points*

Metal	Crystal structure	Melting point °C	Solidification shrinkage (%)	Total shrinkage (%)
Ag	fcc	962	3.8	10.99
Al	fcc	660	6.0 ÷ 7.14	11.66
Au	fcc	1063	5.1 ÷ 5.47	11.0
Bi	rhomb	271	−3.35 ÷ −3.32	-2.73
Cd	hcp	321	3.8 ÷ 4.7	7.18
Cu	fcc	1083	4.1 ÷ 5.3	10.7
Ga	orthorhombic	30	−3.2	-3.05
In	fct	156	1.98 ÷ 2.0	3.8
Mg	hcp	651	3.1 ÷ 4.1	8.6
Ni	fcc	1453	5.11 ÷ 5.4	10.67
Pb	fcc	327	3.22 ÷ 3.56	8.58
Sb	rhomb	631	−0.9 ÷ 0.8	2.95
Si	diam	1410	−9.6 ÷ −2.9	-6.26
Sn	tetrag	232	2.51 ÷ 2.6	4.1
Zn	hcp	420	4.08 ÷ 4.3	7.9

(https://www.researchgate.net/figure/Shrinkage-of-selected-metals_tbl4_276481998)
Note 1) exact values of % solidification depends from the cleanliness of a metal,
2)sign (-) means that the particular metal does not shrinks but expands during solidification.

Shrinkage shows the influence not only on changing dimension but also on shape, especially in walls with different position and thickness, some pretty simply examples are shown in Fig. 5, either on the surface (when metal sinks) or inside the wall (as voids/porosity). No doubt that both macro- and microcavities lead to the decreasing of mechanical properties of castings.

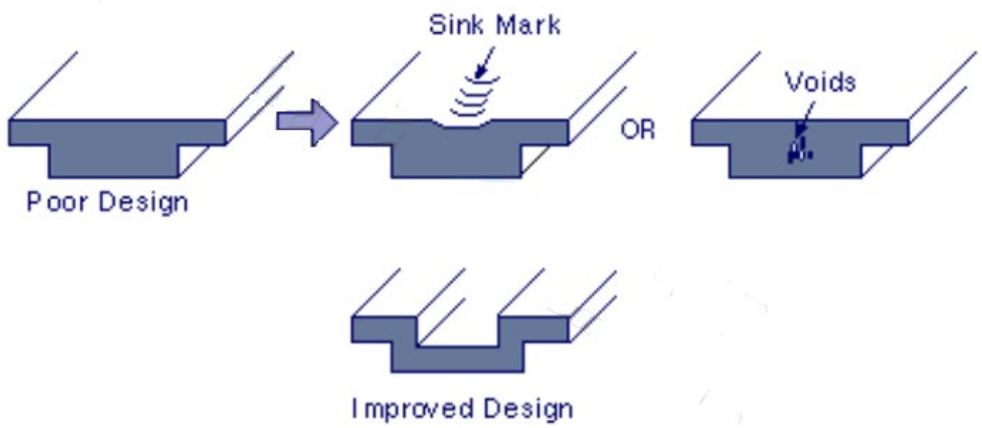


Fig. 5. *One example in designing of walls at casting against shrinkage*

How shrinkage looks-like in many shapes at one wall is shown in Fig. 6.

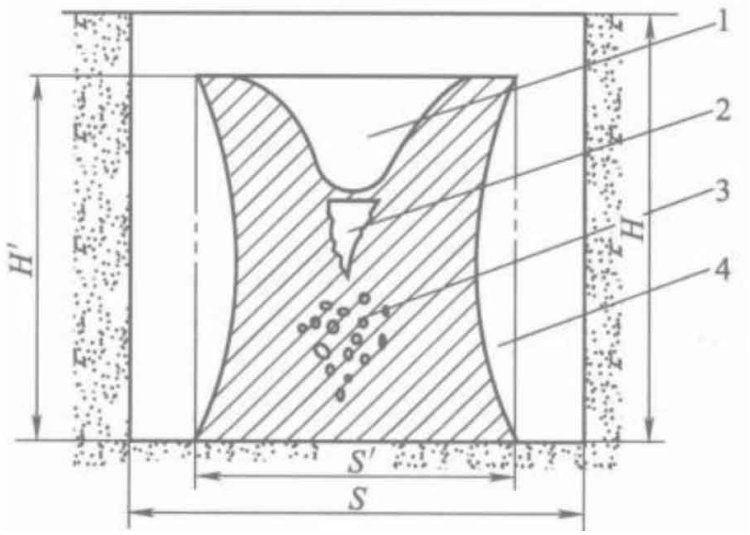
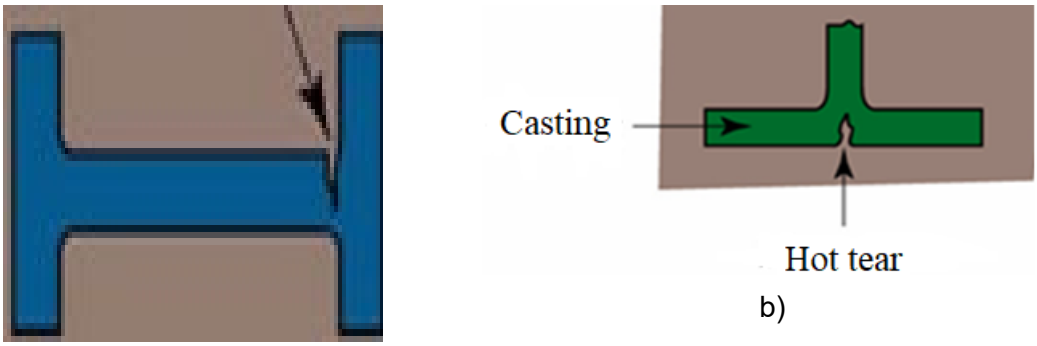


Fig. 6. *Ilustration of shrinkage types at casting wall*
1-open cavity, 2-closed cavity,. 3-porosity and 4-shrinkage/sinking of the wall

If shrinkage remains uncontrolled than it´s undesirable not only for designers but also for usage. Sinking the surface may have the influence on general appearance of the object, and farther similar behavior (or problems) may be found not only during casting but also after welding or brazing.
The appearance of residual stresses at castings also is influenced by the shrinkage, so sometimes those residual stresses are the main reason for cracking. Such cracking may be monitored as their appearing, i.e. as semisolid cracking. Two examples of how the shrinkage during solidification periode may affect on the cracking, also called hot tear, into the casted material are shown in Fig. 7.



a) b)

Fig. 7. *Solidification as a reason for forming*
a) crack at casting with crossed walls and b) hot tear

From the foundry technology, cracks commonly are forming when thin and thick sections are crossed. as shown in Fig. 7a), and similar explanation is for the case from Fig. 7b). It is frequently considered that stresses at castings are in elastic region, but it was not always thrue. In fact, cracks were formed when stress overcome the elastic limit. The uncontrolled residual , however, may have the harmful effects on the operation periode of such element, also for the etnire equipment. These phenomena usually appeared when the solid fraction reaches the 85-95% of the total volume.
The position of shrinkage from Fig. 7b) may be similar to the cases in welding or brazing, when affecting on the visual appearance.
The values of dilatation in wires may be concerned also at quite different applications than casting, as in temperature measuring based on thermoelectric principles, when may be used various materials at interval from -260 up to 2500^0C [9-11].

CONCLUSION

Sometimes, the shrinkage is considered as a kind of casting defect. The shrinkage effects are the largest just at a solidification periode, but should be considered at the entire periode of cooling, it means that begun from the liquid state, than during crystalization and finely at a solid state – to the room temperature. It seems that the last one periode is the most studied, even to subzero treatment.
Shrinkage and produced thermal stresses are the main contributors to the hot cracking, at castings as well at welded joints, rarely after brazing, but frequently during heat.treatment operations. So, the shrinkage phenomenon could not be considered as behaviour only at a short periode of material cooling.
However, the forming of residual stresses is pretty complex from various aspects, including a shrinkage, no matter where they are appeared: at casting, forgings or welded components.

REFERENCES

[1] Šuman H., Metalografija, in Serbian, Beograd 1968, ed. Zavod za izdavanje udžbenika Srbije, p. 69-75; 564-565.
[2] GellerYu.A.,RakhstadtA.G., Science of materials, Moscow 1977, ed. Mir, p. 117-127.
[3] Sedlaček V., Non-ferrous metals and alloys, Amsterdam 1986, ed. Elsevier, p. 61-112.
[4] SchulzeG.E.R., Metallphysik, in Russian, Moskva 1971, ed. Mir, p. 163-182.
[5] B. Kočovski: Theory of casting, in Serbian, Belgrade University, ed. Technical faculty Bor, Bor 1994, p. 93-105; 143-163.
[6] LahtinYu., Engineering physical metallurgy and heat treatment, Moscow 1979, Mir Publishers, p. 38-52.

[7] LagerstedtA. On the shrinkage of metals and its effect in solidification processing, doctoral thesis, Stockholm 2004, Royal Institute of technology
[8] MalevičJu.A., SamojlovičJu.A., Teplofizičeskie osnovi zatverdevanija otlivok i slitkov, in Russian, Minsk 1989, Višejšaja škola, p. 5-68; 179-198.
[9] MoravčikR., Štefanikova M., ČičkaR., Čaplovič Lj., KocúrovaK., ŠturmR., Phase transformations in high alloy cold work tool steel, Strojniški vestnik – J. of mechanical engineering, 58/2012/12, p. 709-715.
[10] KramaruhinJu.E., Pribori dlja izmerenija temperaturi, in Russian, Moskva 1990, Mašinostroenie, p. 6-42.
[11] LivšicB.G., LilevA.S., Fizičeskie metodi issledovnija (teplovie, objemnie, električeskie, magnitnie), in handbook. Metallovedenie i termičeskaja obrabotka stalji, in Russian, Moskva 1983, Metallurgija, p. 287-292.

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IDENTIFICATION OF KEY LEAN TOOLS IN THE AUTOMOTIVE INDUSTRY

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Abstract: This paper aims to emphasize the effective application of Lean philosophy as a strategic approach for achieving operational excellence, by presenting contemporary examples and best practices of Lean implementation within the modern automotive industry. The study focuses on identifying and analyzing Lean tools that significantly impact the improvement of business processes. The provided examples and analyses are intended to offer practical guidelines for organizations striving to improve their operations, as well as to contribute to a clearer understanding of Lean tool application in real-world settings.
Key words: Lean philosophy, automotive industry, production flexibility, production efficiency

INTRODUCTION

The modern, dynamic market, rapid technological progress, and increasingly complex business requirements have forced organizations to constantly adapt to changes. In this context, flexibility becomes a key competitive advantage, and achieving it requires the adoption of modern tools and approaches to continuous improvement. For the successful implementation of the Lean philosophy in the organizations, improvement should not be viewed only as a technical task but primarily as a cultural and strategic process. Individuals, teams, and organizations need to embrace the philosophy as an integral part of their work approach and mindset in an increasingly demanding market. Continuous improvement is possible through rigorous and persistent reduction of common causes of variation around the desired performance level, within a stable process [1]. The high degree of prevalence and diverse applicability of the Lean philosophy underscore its universality and adaptability, highlighting the need for further scientific research across various contexts.
The motivation for conducting this study resulted from the increasing interest of organizations in improving their processes through minimal investments and maximizing the utilization of existing resources.

Subject and aim of the research

The subject of this paper is the Lean philosophy and the practical application of Lean tools in the production processes of a company engaged in manufacturing parts for the automotive industry. The paper examines how specific Lean tools influence production processes and all related activities, including work organization, production time, and the quality of the final product. The main objectives of research are:

- identification of key Lean tools utilized in production systems within the automotive industry,
- demonstrate practical application of Lean tools through industry examples,
- evaluate, based on the given examples, the impact of these tools on key performance indicators (KPI) in production - cycle time, inventory, productivity and quality.

STATE OF RESEARCH

The first significant scientific insight into the application of the Lean concept in manufacturing was provided by *Womack, Jones* and *Roos* in 1990, in their book „The Machine That

Changed the World", where Toyota stands out as an example of highly efficient production [2]. Their studies later confirmed that the implementation of Lean tools such as 5S, Kaizen, JIT, Kanban, and TPM leads to:

- inventory reduction;
- cycle time reduction;
- improved product quality;
- increased customer satisfaction.

The essence of Lean philosophy is to reduce the time between the order and receipt of money by eliminating losses [3]. Numerous studies also emphasize the challenges in implementing the Lean philosophy. According to the *Bhasin* and *Burcher*, Lean implementation in practice often faces significant difficulties. Some of the common barriers are [4]:

- employee resistance to change;
- lack of education and understanding of Lean business culture;
- improper implementation due to insufficient expertise and lack of method knowledge (e.g., only visual changes without deeper analysis);
- poorly measured performance and misrepresentation of results;
- inadequate communication and lack of teamwork;
- the complexity and depth of changes required by Lean, which can cause fear and uncertainty among employees.

Recent literature has focused on the integration of Lean and digital technologies such as [4]:

- IoT and sensors for real-time scrap tracking;
- digital Kanban boards;
- usage of Big Data analytics for more efficient decision-making within the Lean framework.

Lean is no longer viewed only as an analog set of tools, but rather as a foundation for the digital transformation of production systems. Lean provides the philosophy and methodology, while digital tools enable faster and more precise implementation of these methods. Together, they create *Lean 4.0* - production model of the future [5]. Integration of Industry 4.0 within the Lean methodology can help overcome existing barriers to its implementation.
Serbian literature regards Lean as a strategic tool for improving competitiveness, but local authors also emphasize the challenges of implementation, such as lack of training, resistance to change, and formal application without true cultural transformation [6].

KEY LEAN TOOLS IN THE AUTOMOTIVE INDUSTRY – APPLICATION EXAMPLES

Application of modern Lean tools in practice helps organizations eliminate scrap in processes, improve efficiency, and enhance the final value of the service or product delivered to the customer. Below are examples of the implementation of some of the most important Lean tools in the industry. All examples are from a company engaged in the manufacturing of automotive parts.[1]

[1] Due to the business confidentiality and professional ethics, certain data in this paper have been partially modified or presented symbolically, and do not reflect actual numerical values. Key elements are intentionally hidden to preserve confidentiality and maintain professional standards.

5S

The 5S method refers to workplace organization and is widely applied in the automotive industry. Below is an example of the 5S principles implementation in a company that manufactures automotive parts. During the production line changeover from one production variant to another, the workplace was organized according to the following principles [7]:

- sort: excess materials and tools were removed, and only the necessary tools were placed next to or within the production line.
- set in order: each tool has a designated place, and tools are arranged in the order of use during production. Labels and color coding are used to identify tool positions.
- shine: daily routine cleaning schedule for the workplace has been implemented.
- standardize: Standard work instructions exist for every task or activity - cleaning, sorting, maintenance - and all employees follow the same standards.
- sustain: there is a department responsible for conducting 5S inspections, and 5S has been established as a criterion in the monthly team evaluations.

The primary advantages of implementing this approach include:

- accelerated tool retrieval,
- reduction in workplace accidents,
- enhanced worker productivity.

Visual Management

Visual management is the practice of visualizing information or displaying requirements with a focus on improving the understanding of business processes [8]. Smart manufacturing systems, integrating the virtual and physical worlds, surpass traditional ways of working.
Figure 1 shows us a system for monitoring the operation of a production line. The system automatically receives signals from software and maps statuses (green - line operating smoothly; red - unplanned downtime; orange – planned downtime). The use of colors enables quick and intuitive identification of the production line's status, and any emerging issue is immediately made visible to all personnel via a large display screen in the production area. Detailed status indicators provide information on whether the cause of downtime is due to machine failure, material shortage, tool adjustment, or other factors. Additionally, the software enables the export of a comprehensive list of all events and issues for detailed analysis (e.g., using the 5Why method). This practical example of "visual management" effectively demonstrates how color functions as an information carrier, allowing everyone, from operators to managers, to quickly perceive and understand the production status without the need to read or analyze detailed reports.

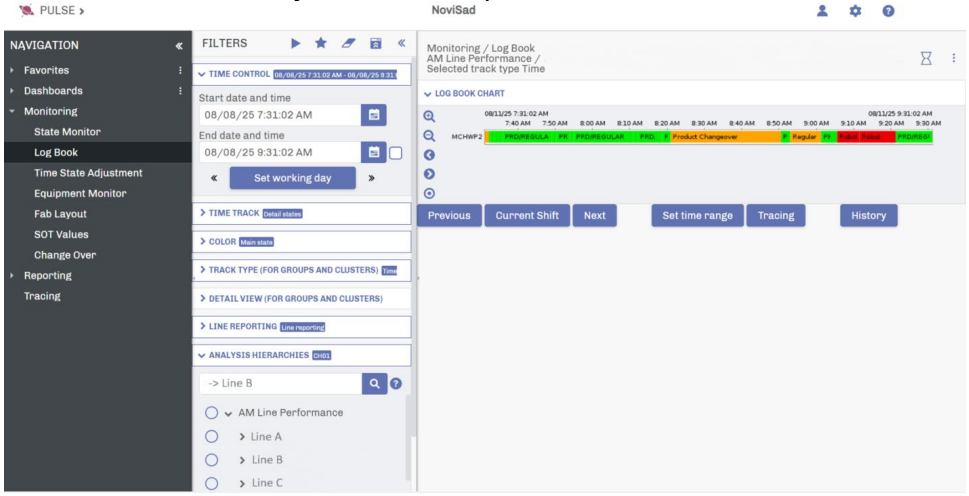


Fig. 1. *System for monitoring and visualizing production line performance*

This example demonstrates how digitalized visual management facilitates transparency in production processes. The integration of clear color coding, time range filters, and detailed downtime classification enables faster detection, analysis, and elimination of losses—an essential aspect of Lean implementation in the automotive industry.
In addition to monitoring and improving equipment productivity and availability, monitoring and improving quality completes the Lean perspective in industry. Figure 2 presents a tool for tracking the total number of good and defective products, the percentage of scrap, main causes of scrap, and other related data.

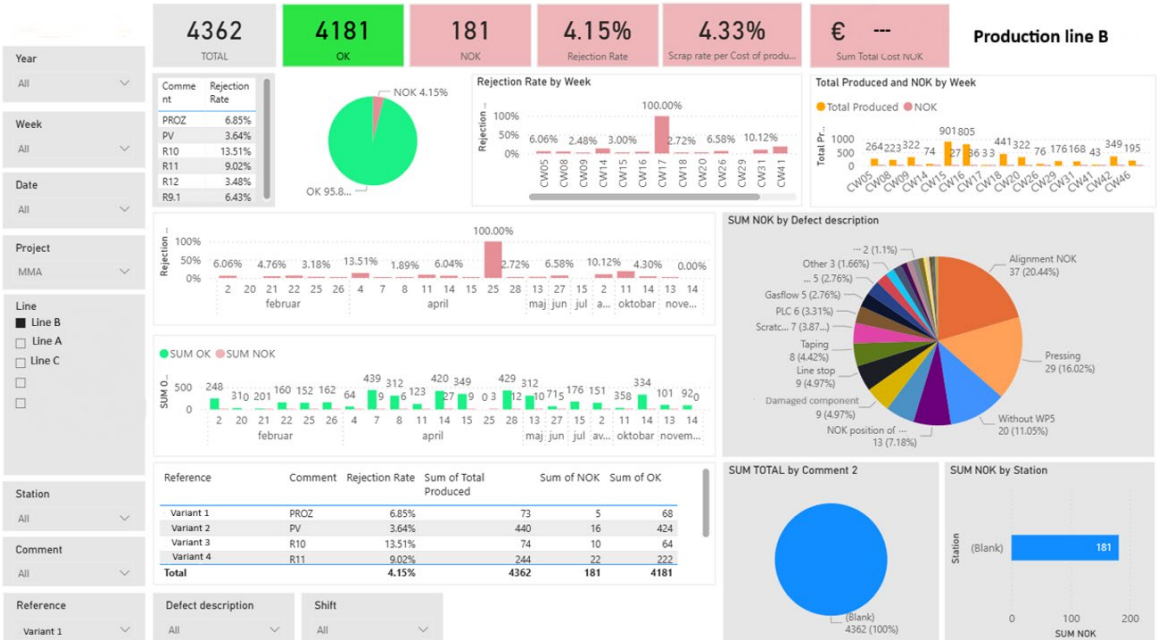


Fig. 2. *System for monitoring quality and identifying primary scrap causes*

The presented example provides a visualization of quality-related data in the form of:

- Pareto chart of defects,
- Quality trends by shifts/days,
- The top 5 causes of scrap,
- The percentage of scrap in total production,
- The correlation of scrap with time, production line, or operator.

Problem Solving Tools

Problem-solving within Lean manufacturing constitutes a fundamental component of the Toyota Production System (TPS). Consequently, contemporary problem-solving tools represent essential techniques for minimizing waste and inefficiencies in production processes. Figure 3 illustrates the software tool "Problem Solving Tool," which is utilized within the Lean framework to systematically address production-related issues. This tool is part of an organizational system designed for standardized tracking and visualization of problem resolutions in manufacturing. User selects the production sector, project, production line, and station where the problem occurs. This primarily enables precise localization of the problem and its connection to the relevant teams and resources. The person responsible for the process inputs the problem solution into the system, making it visible to all individuals involved in the respective process and production line. In cases where the same issue reoccurs, responsible personnel can refer to the previously documented and implemented solution, thereby avoiding additional time loss. Problems are categorized by type

(mechanical, electrical, software, etc.), which facilitates root cause analysis and supports prioritization in problem resolution.

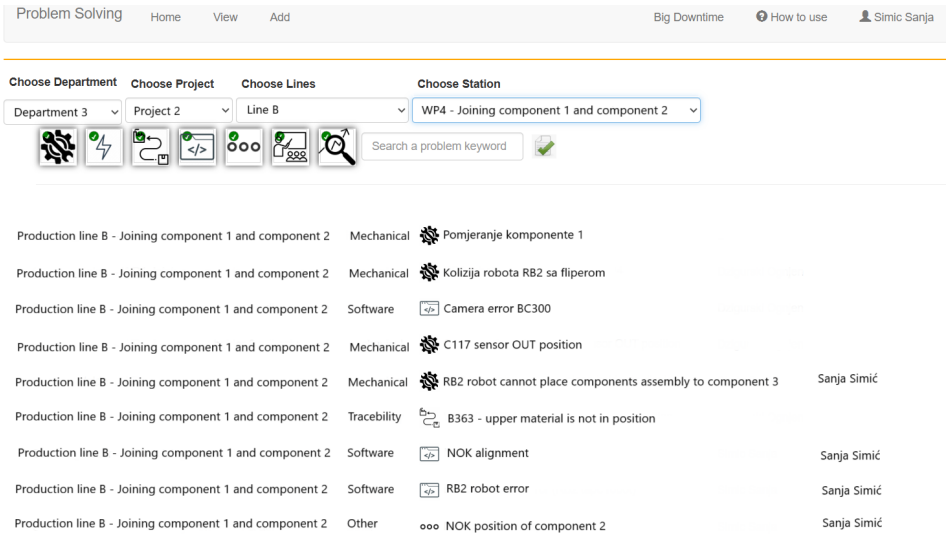


Fig. 3. *Software tool for problem solving and solution strategy presentation*

Single Minute Exchange of Dies - SMED

The ability of individualized and customized production has become a key success factor in today's globalized and digital business environment. Customers strive to receive products customized to their specific needs. These high customer expectations have led to an increase in product variety and complexity. SMED (Single Minute Exchange of Dies) is used to reduce the time required for tool changes or machine adjustments during switching production from one product to another, in order to increase flexibility, productivity, and process efficiency. Generally, SMED aims to standardize and simplify the operations [9]. Figure 4 shows an automated changeover monitoring system, which monitors tool and material changes on the production line during the transition between production variants. This process is critical for efficiency, as improper or untimely execution can lead to delays, errors, and reduced overall productivity. The use of an automated system enables visual tracking of the changeover status and individual steps, reduces the time needed to perform all actions, minimizes human error, and increases quality and safety. System has enabled the reduction of changeover times to approximately 30 minutes for the most complex variants, while simpler changeovers can be completed in 10 minutes. Sections that indicate the product type, changeover steps, current status, and other relevant information are displayed on the HMI screen.

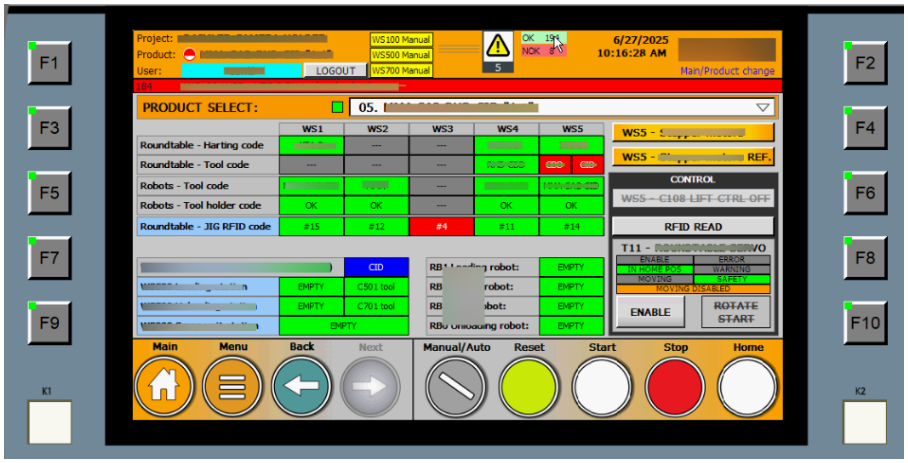


Fig. 4. *Automatic changeover tracking system*

Implementation of such solutions in modern manufacturing is part of the broader concept of Lean philosophy and Industry 4.0, both of which aim to optimize resource usage, support digitalization, and improve efficiency through smart systems.

Poka-Yoke

The Poka-Yoke tool ensures that a component can only be placed in the correct way, thereby eliminating the possibility of operator error. If the component is not properly positioned, system automatically stops the process and gives a warning signal. This is a fundamental principle in Lean manufacturing - detecting problems in real time and automatically stopping the system. Figure 5 shows the method of positioning the tray with components inside a drawer. The highlighted element displays "Poka-Yoke corner" which ensures correct tray placement and prevents errors. There are four corners for positioning: one fixed (4) and three adjustable (3). The fixed corner guarantees that tray can only be placed in a specific orientation.

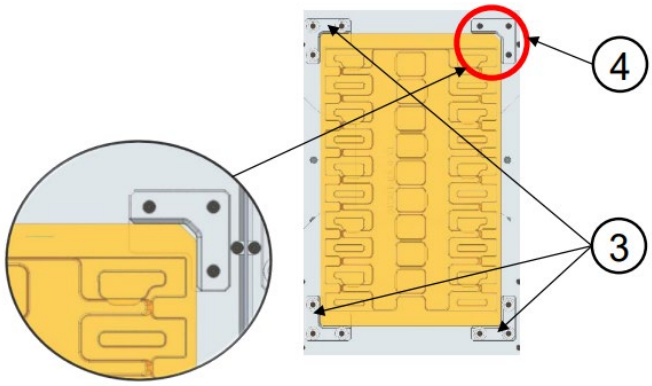


Fig. 5. *Application of the Poka-Yoke system for ensuring correct tray positioning in a drawer*

This method of guiding and positioning allows each tray to be placed correctly and consistently, without the need for additional operator checks or training. As a result, work quality is improved, and potential errors are eliminated. The core philosophy of Poka-Yoke method is respect for human capability and intelligence. During repetitive operations which depend on vigilance or memory, poka-yoke may save time and release the mind of worker for operations more creative and increase their value [10].

Jidoka

The Jidoka principle in manufacturing is typically triggered by quality issues in products and implies stopping the production line until the problem is effectively resolved. A common example of Jidoka application in modern production lines is the automatic stop of the process after three defective products are detected consecutively. The production line is equipped with an automatic inspection system that sends good products to the output station and defective products to the scrap station. When the first defective product passes through the system, error is recorded, but production does not stop immediately. However, if three defective products are detected consecutively, the system automatically:

- stops the production line;
- activates the light and sound signal;
- displays a notification message to the responsible person.

This approach enables quick response to potential problems in the process (e.g., worn tools, incorrect materials, errors in machine parameters) and prevents further scrap parts production.

5Why

This Lean method requires employees to identify the root cause of a problem, preventing the company's engineering team from settling for superficial solutions and forcing them to address issues permanently. It is a very simple analytical method that can be used without any statistical analysis. Below is an example of applying the 5 Why method to the case of bad alignment between two components at the one station within the production line.
Problem description: In the process at the WP4 station (Joining Component 1 and Component 2), bad alignment between Component 1 and Component 2 was observed. This led to a defective output product, activation of Jidoka, and stoppage of the production line. The problem-solving analysis and its results are presented in Table 1.
In this case, although the initial conclusion after the appearance of defective parts was that there was a problem with the offset, the analysis showed that the real cause was the lack of proper work procedures. Additionally, during the design and implementation of this change on the production line, it was not considered that the new gripper, due to a more complex manufacturing process, would behave differently in the production environment. Despite having the same tool dimensions and design, the gripper reacted differently to working conditions, and after a short period, a micro-shift in the tool's coordinate system occurred, resulting in an incorrect offset.

Table 1. *Root cause analysis of bad alignment using the 5Why technique*

No.	Question	Answer
1	Why did bad alignment occur between Component 1 and Component 2?	Because the offset in the X direction was incorrectly set.
2	Why was the offset in the X direction incorrectly set?	Because a new gripper was implemented, of the same design, but it proved to be less stable than the previous one.
3	Why did the new gripper cause the offset problem?	Because after installing the new gripper, the position was not checked and adjusted.
4	Why was the position not checked and adjusted after installation?	Because there was no defined standard procedure for position verification after modifications.
5	Why was there no such standard procedure?	Because current procedures do not require manual measurement, inspection, and adjustment as a mandatory step after changes on the production line, unless there are mechanical modifications to the tool.

Total Productive Maintenance

In modern manufacturing organizations, the development of a strong maintenance culture is essential for improving production efficiency and operational success. A prime example is the implementation of Total Productive Maintenance (TPM), a key concept rooted in Japanese manufacturing philosophy that promotes comprehensive maintenance and equipment management. TPM objective is to maximize efficiency and productivity by involving all employees, from operators to planners, engineers, supervisors, and top management, in proactive activities. Practical industrial application of TPM is through the SAP PM (Plant Maintenance) module. This module supports the planning, execution, and monitoring of all maintenance activities in a digitalized and automated manner. By enabling the creation of maintenance plans, work orders, and detailed recording of interventions, SAP PM helps organizations simplify maintenance workflows and reduce equipment downtime. Integration of SAP PM with inventory management ensures efficient spare parts handling, which minimizes delays and enhances production reliability. In an industrial setting, SAP PM allows maintenance teams and managers to quickly access maintenance schedules, avoid overlapping activities, and assess technician's workloads. Preventive maintenance routines managed through SAP contribute directly to reducing unplanned failures, extending life of equipment, and lowering overall maintenance costs. SAP can be integrated with quality control, production, and energy management systems, allowing a holistic approach to maintenance and manufacturing processes. This integration improves communication between different departments and supports faster response to potential issues.

CONCLUSION

The presented case studies illustrate how Lean tools support continuous improvement in real industrial settings. At its core, Lean methodology emphasizes the creation of greater value through the efficient use of fewer resources. The basic Lean framework involves methodical cost reduction and scrap elimination across entire value streams, rather than just isolated points, creating processes that require less human effort, space, capital, and time to produce goods and services at significantly lower costs and with far fewer defects compared to traditional business systems. In modern manufacturing systems, Lean has emerged as one of the most effective concepts for improving and increasing the competitiveness of organizations. This article, in addition to reviewing existing literature, presents practical applications of some of the most important Lean tools used in the contemporary automotive industry. Through concrete examples, the application of tools, approaches, deeper understanding, and problem-solving methods in modern industry are explained. It is important to note that insufficient or incorrect understanding of Lean, resistance to change, and lack of a long-term strategy significantly affect the efficiency of its implementation. Therefore, successful implementation and sustainable application require not only technical knowledge and tool introduction but also cultural transformation, involvement, and discipline of all employees.

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REFERENCES

[1] Howard S. Gitlov.: „A Guide to Lean Six Sigma Management Skills". CRC Press, Taylor&Francis Group, London-New York.
[2] Womack, J.P., Jones, D.T., Roos, D.: „The Machine That Changed The World". Free Press, New York, 2007.
[3] Tamás, P., Varga, A.: „The role of proposal management systems in the production and service". Journal of Production Engineering, Vol. 24, No. 1, pp. 65–68, 2023.
[4] Bhasin, S., Burcher, P.: „Lean viewed as a philosophy". Journal of Manufacturing Technology Management, Vol. 17, No. 1, pp. 56–72, 2006.
[5] Tortorella, G. L., Fettermann, D.: „Integration of Industry 4.0 and lean manufacturing: A systematic literature review". Journal of Manufacturing Technology Management, Vol. 29, No. 6, pp. 910–929, 2018.
[6] Mandić, J.: „Razvoj modela za unapređenje proizvodnog procesa i smanjenje uticaja gubitaka neuravnoteženosti i preopterećenja – Lean 3M". Doktorska disertacija, Fakultet tehničkih nauka, Novi Sad, 2019.
[7] Palange, A., Dhatrak, P.: „Lean manufacturing a vital tool to enhance productivity in manufacturing". Materials Today: Proceedings, Vol. 46, Part 1, pp. 729–736, 2021.
[8] Eaidgah, Y., Arab Maki, A., Kurczewski, K., Abdekhodaee, A.: „Visual management, performance management and continuous improvement: A lean manufacturing approach". International Journal of Lean Six Sigma, Vol. 7, No. 2, pp. 187–210, 2016.
[9] Ulutas, B.: „An application of SMED methodology". International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering, Vol. 5, No. 7, 2011.
[10] Dudek-Burlikowska, M., Szewieczek, D.: „The Poka-Yoke method as an improving quality tool of operations in the process". Journal of Achievements in Materials and Manufacturing Engineering, Vol. 36, No. 1, pp. 95–102, 2009.

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APPLICATION OF CAD TOOLS IN DESIGNING COMPLEX MECHANICAL ASSEMBLIES

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Abstract: This work presents the application of CAD tools on the example of a hydraulic lifting table. The mechanism was modeled in Autodesk Inventor and analyzed through motion simulation and static calculation using the finite element method. The results indicate that CAD software accelerates development, reduces costs, and enables timely corrections within the virtual model.
Key words: *stress analysis, motion simulation, finite element method (FEM), Computer-aided design (CAD)*

INTRODUCTION

The development of modern industry is unimaginable without computer tools that enable fast and precise design, analysis, and optimization of technical systems. According to Budynas and Nisbett, the integration of computer-aided methods has fundamentally transformed engineering design by enabling more reliable and efficient solutions [1]. A key role in this process is played by CAD (Computer-Aided Design) software, which has become a standard in mechanical engineering. Its application includes creating 3D models, generating technical documentation, and connecting with tools for motion simulation and stress analysis. As Norton emphasizes, the combination of CAD modeling with analytical methods significantly improves the ability of engineers to predict system behavior during the design stage [2]. This significantly reduces product development time, increases construction accuracy, and improves quality control.
Designing complex assemblies with many interconnected parts requires ensuring functionality, reliability, and cost-effectiveness at the same time. Modern CAD software provides engineers with the ability to test such assemblies virtually, thereby reducing the need for physical prototypes and lowering development costs [3]. In this context, CAD software is an indispensable tool, allowing quick validation of ideas and precise engineering decisions.
The aim of this paper is to present the importance of CAD programs in the development of constructions with complex mechanical assemblies. As a case study, a hydraulic lifting table, shown on Fig. 1, was modeled using CAD tools, followed by motion simulation and static stress analysis. This type of lifting table is used for raising heavy loads to an ergonomic height, allowing the operator to work on them more efficiently. Based on the obtained results, the advantages of this approach are discussed in comparison to traditional design methods.



Fig. 1. *Hydraulic lifting table*

CAD TOOLS AND THEIR ROLE IN ENGINEERING DESIGN

CAD tools occupy a central role in modern engineering design, as they enable the creation, analysis, and modification of complex constructions within a digital environment. Their development and widespread adoption have significantly accelerated the design process and improved the quality of technical documentation. By using CAD software, engineers can develop 3D models, quickly implement design changes, and visually demonstrate the operation of complex assemblies, which was previously difficult to achieve using traditional methods.
A particularly important feature of CAD tools is the integration of models with calculations and simulations. Within CAD software and integrated environments, it is possible to perform motion analyses, load calculations, as well as detailed stress and deformation analyses using the FEM [1]. This allows the design to be evaluated during the development phase, reducing the need for physical prototypes and accelerating product development.
Modern CAD tools, such as Autodesk Inventor, SolidWorks, CATIA, and PTC Creo, offer modules for kinematic and dynamic simulations of assemblies, as well as static and modal analyses [4]. Stress and deformation analyses allow engineers to identify critical areas in the design and optimize geometry or materials before production [2]. This approach not only increases the safety and reliability of the construction but also contributes to cost reduction and shorter development time. Fig. 2 illustrates the main stages of construction development using CAD tools.

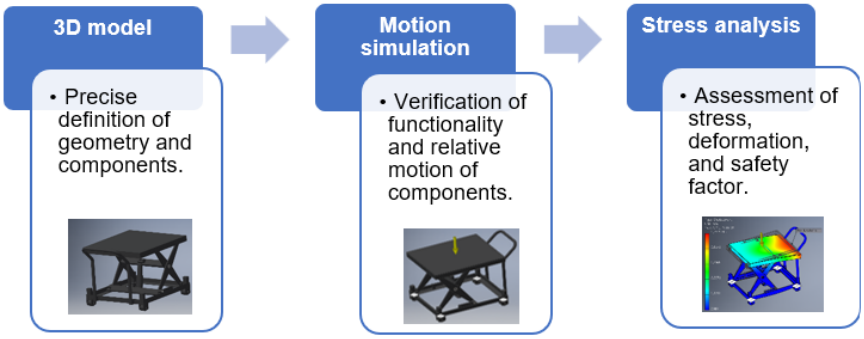


Fig. 2. *Main stages of construction development using CAD tools*

In industrial practice, the use of CAD tools combined with simulations and calculations provides multiple advantages. It allows testing of various design variants under different operating conditions, enabling performance optimization and extending the product's service life [5, 6]. In this way, CAD becomes a fundamental tool not only for design but also for the validation and optimization of complex mechanical assemblies.

MODELING AND ANALYSIS OF THE HYDRAULIC LIFTING TABLE STRUCTURE

Creation of the 3D Model

In the first phase of the work, it is essential to create a 3D model of the structure, which serves as the foundation for all subsequent simulations and calculations. The model was developed using Autodesk Inventor, one of the most widely used CAD tools in industry today, due to its intuitive interface and the ability to integrate with various analysis modules. At this stage, the structure is precisely defined through all necessary dimensions, shapes, and the relationships between components. Special attention is given to accurately representing joints, as these areas often constitute critical zones in terms of loads and stress.
Characteristics of the hydraulic lifting table:

- Work surface: 800 x 1000 mm
- Working height: 850 mm

- Load capacity: 500 kg
- Structure weight: 220 kg
- Minimum height: 250 mm
- Lifting/lowering time: 15 seconds

The main components of the hydraulic lifting table are shown on Fig. 3.

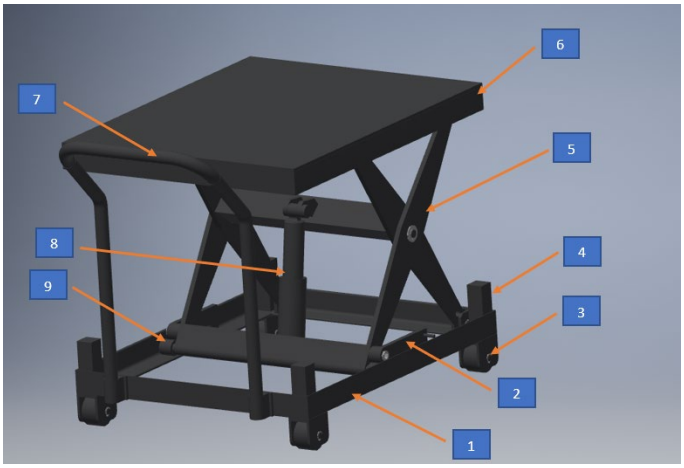


Fig. 3. *Main components of the hydraulic lifting table*

1. Lower frame
2. Safety brake
3. Wheels
4. Minimum height limiter
5. Scissor mechanism
6. Upper frame with plate
7. Handles for moving the hydraulic table
8. Hydraulic cylinder
9. Lower rollers

Preparation for Analyses

After creating the 3D model, the next step is to prepare the structure for analyses. This stage involves checking the geometry and removing any unnecessary details that do not affect the simulation results but could increase the complexity of the finite element mesh and thus prolong computation time [6]. Additionally, the materials of all components are defined, with emphasis on using realistic mechanical properties (elastic modulus, yield strength, Poisson's ratio, etc.) to ensure reliable results. Autodesk Inventor allows easy selection of materials from the built-in library, with the option to enter custom data when needed. For the hydraulic lifting table, different materials were applied: standard structural steels were used for the supporting frame, while the moving parts (rollers and shafts) were made of improved steel to increase resistance to load and wear.

Motion Simulation and Static Analysis Setup

During the simulations, special attention is given to motion analysis and static calculation of the structure. Motion simulation allows verification of the mechanism's functionality and analysis of its operating dynamics, enabling the identification of potential collisions, blockages, or irregularities in system operation [7].

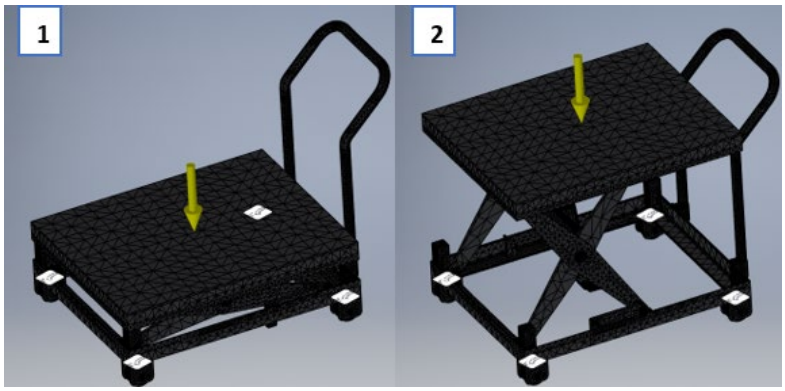


Fig. 4. *Fixed points and force load of the hydraulic table in the lower (1) and upper (2) positions*

For the purpose of static stress analysis, the structure is fixed at the support points, while appropriate loads corresponding to real working conditions are applied to relevant components, as shown on Fig. 4. In our case, the structure must support a load of 500 kg, corresponding to a force of 5000 N. It is also necessary to define a suitable FEM, where a finer mesh in critical areas provides more accurate results [8, 9]. The software then calculates the distribution of stress, deformation, and displacement.

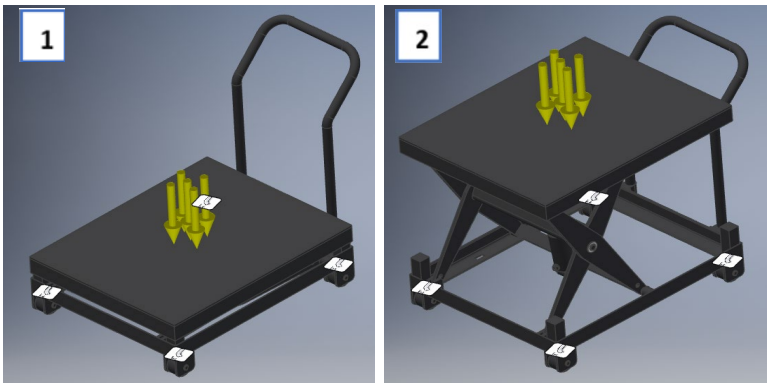


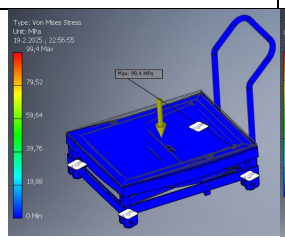
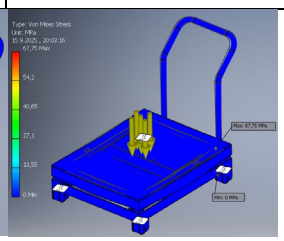
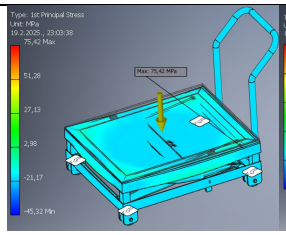
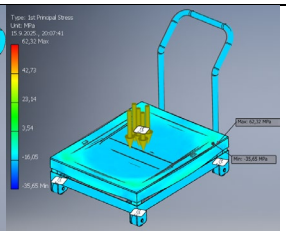
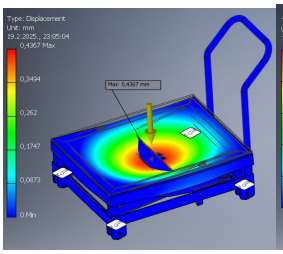
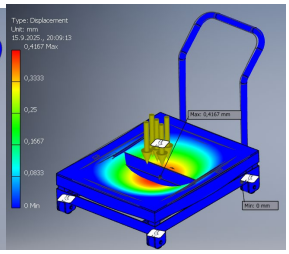
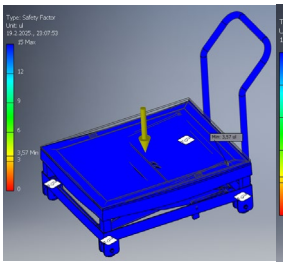
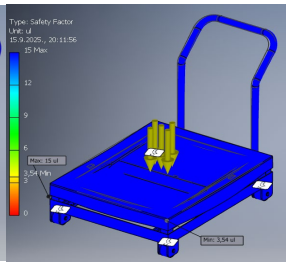
Fig. 5. *Fixed points and distributed loads of the hydraulic table in the lower (1) and upper (2) positions*

In addition to the force load applied directly to the platform surface, an alternative approach was carried out using distributed load, represented as surface pressure equivalent to the weight of 500 kg acting on the working platform of the hydraulic lifting table, as shown on Fig. 5. This enabled a comparative assessment of the results obtained under the two loading methods, providing a more comprehensive evaluation of the structural behavior.
The structure is also subjected to the weight of the hydraulic lifting table components, which is applied in the CAD program using the "Gravity" function.

RESULTS AND DISCUSSION

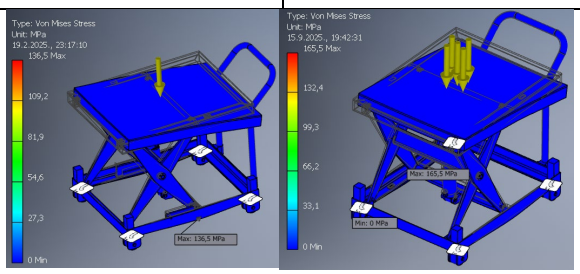
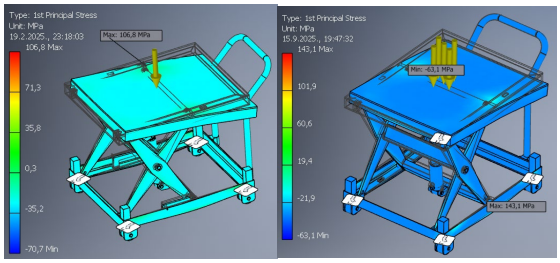
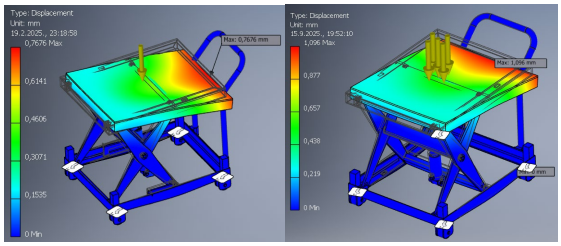
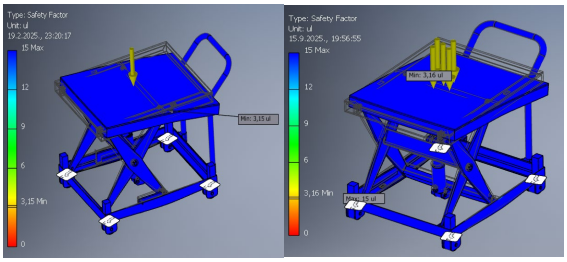
The results obtained from the static analysis in Autodesk Inventor provide a detailed insight into the behavior of the structure under load. Based on these results, critical areas requiring additional reinforcement or geometry modifications can be identified. Comparing the results with the allowable material limits confirms whether the structure meets load-bearing and safety requirements [10]. The obtained data serve as a basis for design optimization and cost reduction, as they allow corrections on the virtual model instead of a physical prototype. In this way, the use of CAD software, such as Autodesk Inventor, directly impacts product quality and development efficiency.
The results of stress and deformation analysis for the hydraulic lifting table in the lower position are presented in Table 1, showing the results for force load (1) and pressure load (2).

Table 1. *Static analysis results for the lowered position of the structure*

Static analysis results for the lowered position of the structure				
Characteristic	**Load image**		**Values**	**Comment**
	1. Force method	*2. Pressure method*		
1.Von Mises Stress (Strain in relation to the yield stress of the material):			Max. stress: 1. 99.4 MPa 2. 67.75 MPa	The max. stress was detected on the upper roller.
2. 1st Principal Stress			Max. stress: 1. 75.42 MPa 2. 62.32 MPa	The max. stress was detected on the upper roller.
3.Displacement (Deflection - deformation)			Max. deflection: 1. 0.437 mm. 2. 0.42 mm	The max. deflection was detected in the middle of the platform. Max. allowed deflection: 3 mm.
4.Safety Factor:			Min. safety factor: 1. 3.57 2. 3.54	The min. safety factor for the force method was detected in the upper roller zone, while for the pressure method it was in the upper scissor shaft (limit: 3).

The results of stress and deformation analysis for the hydraulic lifting table in the upper position are presented in Table 2, showing the results for force load (1) and pressure load (2).

Table 2. *Static analysis results for the raised position of the structure*

Static analysis results for the upper position of the structure				
Characteristic	**Load image**		**Values**	**Comment**
	1. Force method	*2. Pressure method*		
1.Von Mises Stress (Strain in relation to the yield stress of the material):			Max. stress: 1. 136.5 MPa 2. 165.5 MPa	The max. stress was detected on the lower roller.
2. 1st Principal Stress			Max. stress: 1. 106.8 MPa 2. 143,1 MPa	The max. stress for the force load method was detected on the upper roller, while for the pressure load method it was detected on the lower roller.
3.Displacement (Deflection - deformation)			Max. deflection: 1. 0.76 mm. 2. 1,1 mm	The max. deflection was observed on the platform edge farthest from the scissors mechanism (limit: 3 mm).
4.Safety Factor:			Min. safety factor: 1. 3.15 2. 3,16	The min. safety factor was detected in the upper roller zone. Allowed min. safety factor: 3.

The stress and deformation analysis of the hydraulic lifting table shows that the structure meets all safety and functional requirements. In the first case, with a concentrated force of 5000 N, maximum stress and deflection remain within allowable limits. Similar results were obtained under a distributed load simulating a 500 kg mass on the work platform.
Comparing the lower and upper positions of the hydraulic mechanism, stress and deflection values differ slightly, but in both positions the structure satisfies the required safety factor and maximum deflection limits. These results indicate that the table design provides sufficient strength and stability.

CONCLUSION

This paper presented the development process of a hydraulic lifting table structure using Autodesk Inventor. To obtain a structure that meets all required criteria, stress analysis was performed multiple times, identifying critical components. These components were optimized by modifying dimensions or materials; for example, the rollers were made from stronger steel with additional heat treatment, improving their mechanical properties.
The final static calculation is presented, in which the structure was already optimized to satisfy the prescribed safety factor and allowable deformations. Stress and deformation analyses were conducted for two types of loads: a concentrated force (Force load) and a distributed load over the platform (Distributed load). In both cases, the structure meets the minimum requirements regarding safety factor and maximum deflection. In addition, kinematic simulations of the hydraulic table's movement were performed to verify that all components function correctly throughout the lifting range. The results, shown through principal stresses, maximum deformation, and safety factor, confirm that the structure can safely carry a load of 500 kg.
The use of CAD software enabled detailed simulation of the mechanism's behavior under load, eliminated potential errors from manual calculations, and significantly accelerated the design and verification process. As a direction for future research, further optimization of the structure is suggested by reducing material thickness or using lighter materials only in areas where the safety factor is significantly higher than 3, which would result in production savings and a reduction of the overall mass of the hydraulic lifting table.

REFERENCES

[1] Budynas, R.G., Nisbett, J.K., *Shigley's Mechanical Engineering Design*, 9th Edition, McGraw-Hill, New York, 2011.
[2] Norton, R.L., *Machine Design: An Integrated Approach*, 5th Edition, Pearson, New Jersey, 2013.
[3] Autodesk Inc., *Autodesk Inventor Professional 2022 – Help Documentation*, Autodesk, 2022.
[4] Beer, F.P., Johnston, E.R., DeWolf, J.T., Mazurek, D.F., *Mechanics of Materials*, McGraw-Hill, New York, 2015.
[5] Hibbeler, R.C., *Mechanics of Materials*, 10th Edition, Pearson, Boston, 2017.
[6] Tabaković, S., *Simulacija kinematike virtuelnog prototipa i primjena CAD/CAE alata*, Mašinski fakultet Univerziteta u Beogradu / Centar za razvoj, Beograd, Srbija, 2016.
[7] Pahl, G., Beitz, W., Feldhusen, J., Grote, K.-H., *Engineering Design: A Systematic Approach*, 3rd ed., Springer, London, 2007.
[8] Kovacevic, D., *MKE modeliranje u analizi konstrukcija*, Belgrade, 2006.
[9] Basa, B.B., *Primjena CAD/CAM sustava u konstrukciji i obradi kućišta motora*, diplomski rad, Fakultet strojarstva i brodogradnje, Sveučilište u Zagrebu, Zagreb, Hrvatska, 2017.
[10] Karagülle, H., *Investigation on the design of double-stage scissor lifts using FEM*, Machines (MDPI) / European research, 2023.

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INTELLIGENT 3D SPACE OPTIMIZATION FOR LOGISTICS OPERATIONS

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Abstract: In modern logistics operations, effective capacity utilization in warehouse, palletizing, and transportation processes is one of the most critical objectives. Manual planning errors, inadequate rule-based approaches, and a lack of integration with enterprise systems are common issues encountered in traditional methods, which increase operational costs, lead to lost time, and negatively impact sustainability goals. This study proposes an intelligent software solution that utilizes heuristic, exact, and metaheuristic algorithms, supported by 3D visualization and ERP/WMS/TMS integration. The proposed system ensures optimal placement of products on pallets, containers, and vehicles, thereby increasing operational efficiency and contributing to the green transformation of logistics.
Keywords: 3D optimization, logistics, heuristic

INTRODUCTION

Increasing competition in global supply chains necessitates reducing costs and achieving sustainability goals in the logistics sector. Minimizing empty spaces, particularly during pallet, container, and vehicle loading processes, provides both economic and environmental benefits. However, current systems largely rely on manual planning or rule-based methods, resulting in inefficient capacity utilization, loading errors, and high operational costs [1].
In recent years, interest in optimization software in the logistics sector has increased as part of Industry 4.0 and digital transformation. Existing methods often rely on manual planning or simple rule-based algorithms. However, these methods are both time-consuming and inadequate for complex product diversity. Furthermore, most of the software used is not integrated with enterprise systems, such as ERP, WMS, or TMS, leading to disruptions in data flow and difficulties with real-time decision-making. Furthermore, sustainability pressures are driving the need to reduce carbon footprints [1-3].
The container and vehicle capacity optimization problem is closely related to the classical 3D Bin Packing Problem (3D-BPP). In the literature, this problem cannot be solved with exact methods in large-scale examples due to its NP-hard nature, so heuristic and metaheuristic algorithms are preferred [4,5]. Especially in the logistics sector, the efficient packing of loads of varying sizes and weights into containers and pallets plays a critical role in both reducing operational costs and ensuring environmental sustainability [6].
The Container Loading Problem (CLP) and the Bin Packing Problem (BPP) are optimization problems that have long been the subject of research attention. While exact methods (e.g., integer programming) were proposed in early studies, computational costs remained very high for large-scale problems [7]. Therefore, in recent years, heuristic and metaheuristic methods (genetic algorithms, tabu search, simulated annealing, etc.) have become increasingly preferred [5,6,8].
Furthermore, incorporating not only theoretical optimization but also real-world constraints into the model has become important. Ignoring factors such as product fragility, stacking rules, weight balance, and regulations reduces the applicability of solutions [9,10].
Recent studies emphasize the need to consider AI-supported optimization approaches in logistics processes in conjunction with green transformation goals [1].

The intelligent 3D optimization platform proposed in this study offers a solution that is both theoretical and applicable in the field. Thus, capacity planning in logistics is no longer merely a tool for reducing operational costs but rather a strategic tool that serves sustainability and digital transformation goals.

MATERIAL AND METHODS

Problem State

In logistics and supply chain management, the Container Loading Problem (CLP) and the Multi-dimensional Bin Packing Problem (BPP) are among the most well-known NP-hard optimization problems [5,7]. The primary objective is to minimize void volume and maximize capacity utilization by placing products of varying sizes and constraints into vehicles, containers, or pallets in accordance with the limited volume, weight, and stacking conditions. This problem directly impacts not only operational efficiency but also cost reduction and sustainability objectives [10].
Mathematically, the problem can be formulated as follows: Products with dimensions (l_i, w_i, h_i), each denoted by $i = 1,2,\dots,n$ must be placed in containers of dimensions (L, W, H). Each product can be placed only once, and additional constraints, such as rotation, weight distribution, or fragility, must also be considered. The main optimization objective is to maximize the total volume used to increase the fill ratio within the container:

$$\max U = \frac{\sum_{i=1}^{n} V_i \times x_i}{V_c}, \tag{1}$$

Here, $V_i = l_i \times w_i \times h_i$ represents the product volume and $V_c = L \times W \times H$ represents the container volume. The decision variable $x_i \in \{0,1\}$ indicates whether the product is placed or not.
However, in real-world scenarios, volume constraints alone are not sufficient. For example, operational constraints such as weight constraints ($\sum w_i \times x_i \leq W_{max}$), product fragility (not placing heavy products on top), and delivery priority must be incorporated into the model [3,9]. This transforms the problem from a classical optimization problem into a highly constrained, multi-objective optimization problem. Therefore, the use of heuristic and metaheuristic methods for solving CLP/BPP provides more applicable and effective results, especially in large-scale logistics operations [8].

Method

The system proposed in this study proposes a multi-constrained, multi-objective optimization approach for optimizing container, pallet, and vehicle capacities in logistics operations. The developed method is based on a hybrid combination of heuristic, exact, and metaheuristic algorithms. The proposed solution method consists of four main components:

Table 1. *Methodological components of the proposed system*

Modules	Descriptions	Methods
Data Preprocessing	Modeling of product dimensions, weights, and operational constraints	Database, preprocessing algorithms
Optimization Engine	Generation of loading plans.	Exact, Heuristic, and Metaheuristic
3D Visualization	Simulation of loading plans and operator support	3D modeling, visualization libraries
Integration Layer	ERP/WMS/TMS integration and reporting	API, web services

Among metaheuristic methods, Genetic Algorithm (GA) and Tabu Search (TS) are particularly prominent. In GA, each chromosome represents the order of placement of products within the container. Crossover and mutation operators enable efficient scanning of the solution space by generating different loading scenarios [10]. In TS, a specific tabu list is maintained for each solution, preventing the algorithm from getting stuck in local optima [8].

RESULTS AND DISCUSSION

In this study, our algorithmic approach consists of preprocessing, constructive, and improvement phases. In the preprocessing phase, the items are sorted based on volume, weight, and stackability criteria, thus narrowing the search space during the placement process. In the constructive phase, an initial solution is generated using potential placement points for the boxes ("pivot points") and maximal space management strategies [8]. In the improvement phase, solution quality is enhanced by applying metaheuristics such as Variable Neighborhood Descent (VND) or GRASP (Greedy Randomized Adaptive Search Procedure) [11, 12].
In the model proposed by Zanchetta (2025), the concept of multi-objective optimization is particularly prominent. Similarly, our study addresses two main objectives:
1. Maximizing volume utilization – reducing transportation costs by minimizing the number of pallets/containers used.
2. Considering fragility constraints – placing loads in accordance with stacking rules to prevent product damage.
The Pareto optimality approach was adopted for optimizing this multi-objective structure, aiming to achieve solutions that balance different objectives [13]. Thus, solutions are produced that consider not only capacity utilization but also operational safety and customer satisfaction. Figure 1 shows an example of single and mixed packaging.

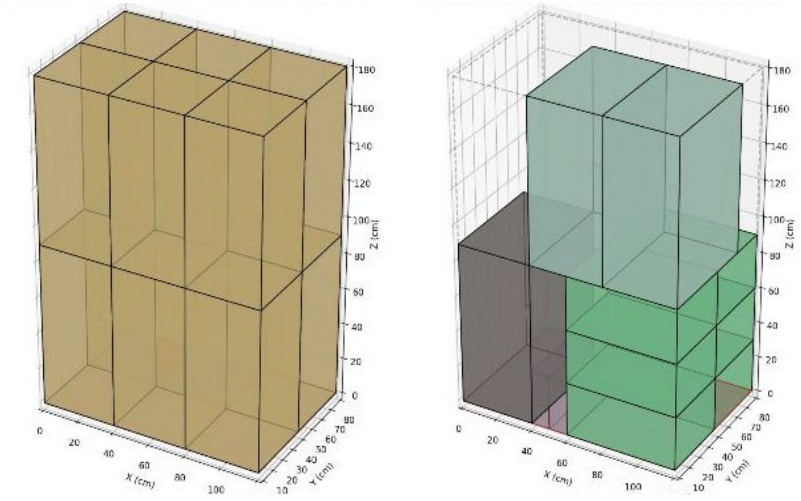


Fig. 1. *An example of single and mixed packaging*

CONCLUSION

This study presents an AI-based software approach that optimizes capacity utilization in logistics operations. Through algorithmic optimization, 3D visualization, and enterprise system integration, the system increases both theoretical efficiency and field applicability. This enables logistics planning processes to be faster, more accurate, more cost-effective, and more sustainable.
Studies demonstrate that logistics optimization systems not only provide cost advantages but can also directly contribute to sustainability goals. Future research is expected to focus more

on the operational flexibility, real-time integration, and environmental impact reduction dimensions of AI-supported optimization models.

Acknowledgments

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REFERENCES

[1] Chen, W., Men, Y., Fuster, N., Osorio, C., & Juan, A. A. (2024). Artificial Intelligence in Logistics Optimization with Sustainable Criteria: A Review. Sustainability, 16(21), 9145. https://doi.org/10.3390/su16219145
[2] Ivanov, D., Dolgui, A., & Sokolov, B. (2022). Sustainable supply chain modeling and risk analytics under disruption risks. International Journal of Production Research, 60(11), 3273–3290.
[3] Wątróbski, J., Sałabun, W., & Karczmarczyk, A. (2019). Green logistics in supply chain management: The potential of fuzzy multi-criteria decision-making methods. Sustainability, 11(12), 3250.
[4] Martello, S., Pisinger, D., & Toth, P. (2000). New trends in exact algorithms for the 0–1 knapsack problem. European Journal of Operational Research.
[5] Bortfeldt, A., & Wäscher, G. (2013). Constraints in container loading – A state-of-the-art review. European Journal of Operational Research, 229(1), 1–20.
[6] Zanchetta, R. (2025). 3D Bin Packing: a new Heuristic approach for real case scenario (Doctoral dissertation, Politecnico di Torino).
[7] Chen, C. S., Lee, S. M., & Shen, Q. S. (1995). An analytical model for the container loading problem. European Journal of Operational Research, 80(1), 68–76.
[8] Crainic, T. G., Gendreau, M., & Potvin, J. Y. (2008). Intelligent freight-transportation systems: Assessment and the contribution of operations research. Transportation Research Part C, 16(6), 512–540.
[9] Gehring, H., Menschner, K., & Meyer, M. (2011). A computer-based heuristic for packing pooled consignments into standard containers. Computers & Operations Research, 38(1), 291–300.
[10] Zhao, Z., Liu, Q., & Lü, Z. (2016). A hybrid algorithm for the three-dimensional container loading problem with practical constraints. International Journal of Production Research, 54(5), 1368–1384.
[11] Feo, T. A., & Resende, M. G. C. (1995). Greedy randomized adaptive search procedures. Journal of Global Optimization.
[12] Hansen, P., & Mladenović, N. (2001). Variable neighborhood search: Principles and applications. European Journal of Operational Research.
[13] Deb, K. (2001). Multi-objective Optimization Using Evolutionary Algorithms. Wiley.

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MODELS OF AI INTEGRATION IN ENGINEERING EDUCATION: A PRACTICAL FRAMEWORK FOR LEARNING OUTCOMES, RETENTION, AND ACADEMIC INTEGRITY

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Abstract: This paper proposes a practical, program-level framework for integrating generative AI into engineering education while safeguarding academic integrity and improving learning outcomes and retention. Drawing on recent evidence from engineering and STEM education, the framework aligns curriculum outcomes with ABET expectations, embeds AI-supported active learning (e.g., retrieval practice, automated feedback), and redesigns assessment to prioritize process evidence and oral/interactive defenses. We describe governance mechanisms, recommended tool chains, and analytics for continuous improvement. A comparative table and implementation roadmap illustrate how departments can sequence adoption across courses and years of study. The approach is intended for resource-constrained programs seeking measurable, ethically grounded gains in performance, persistence, and fairness.
Key words: engineering education, generative AI, learning outcomes, retention, academic integrity, assessment design

INTRODUCTION

Engineering programs operate under simultaneous pressures: rapid AI capability growth, industry demand for AI-literate graduates, and external accountability via accreditation. As programs redesign learning environments, three tensions recur: (I) how to maintain rigorous conceptual understanding when assistance tools shorten problem-solving paths; (II) how to preserve fairness and academic integrity without an unproductive arms race with detection; and (III) how to deliver measurable gains in outcomes and persistence that justify institutional investment [1].
This paper is positioned as a pragmatic blueprint rather than a technology showcase. We delineate governance choices (what is permitted, expected, and assessed), instructional patterns (how AI augments-not replaces-core practices), and measurement (how retention, attainment, and integrity are tracked over time) with exemplars aligned to ABET outcomes and contemporary guidance from national and international bodies [2].
Generative AI is moving from pilot use to routine practice across higher education, including engineering programs. Institutions now face pressure to equip students with AI fluency while ensuring mastery of core principles and ethical practice [1]. At the same time, accreditation bodies require programs to demonstrate attainment of program outcomes and effective assessment practices, which must be reconciled with the realities of AI-enabled learning [1].

BACKGROUND AND RELATED WORK

A complementary meta-analysis across 51 (quasi)experimental studies reports large effects on performance and moderate gains in perception and higher-order thinking, and highlights moderators such as learning model and role of ChatGPT, underscoring the need for scaffolded design [3].
Recent meta-analytic evidence indicates positive average effects of ChatGPT on academic performance and higher-order thinking, with substantial heterogeneity across course type and duration; this supports measured, context-sensitive adoption rather than blanket policies [4].

Syntheses across STEM and engineering education show heterogeneous effects: AI excels at code generation, structure for lab reports, and formative hints, but can hallucinate sources, mis-handle units, and propagate subtle misconceptions in modeling tasks. Consequently, scholars recommend structured tool alignment (match task → tool → evidence), human-in-the-loop verification, and explicit instruction on prompt design and result checking [5].

On integrity, converging evidence warns that empirical evaluations show that AI-text AI-text detectors have documented limitations (precision/recall trade-offs and false positives) (e.g., false positives) and can be inequitable, especially for non-native writers; consequently, design-based integrity strategies are preferred (higher false positives for L2 writers), and that design-based approaches process evidence, oral defenses, and authentic tasks—outperform surveillance-heavy strategies in both fidelity and student trust [6,7]. illustrative policy frameworks (e.g., sector bodies and ministries) converge on disclosure norms and instructor-designed safeguards rather than blanket bans [6,7].

Recent reviews in engineering education report rapid growth of AI-powered tools for coding assistance, simulation, lab report drafting, and formative feedback. Studies comparing common assistants (e.g., ChatGPT, Copilot, Gemini, Wolfram) find differential strengths across task types, suggesting the need for structured tool alignment to course outcomes [6].

Evidence from STEM learning science indicates that retrieval practice with spacing can increase durable learning, and emerging work shows that generative AI can scale the creation of retrieval prompts and adaptive practice sequences [2].

Concurrently, multiple universities and national bodies caution against reliance on AI detectors and instead recommend assessment redesign and explicit policy guidance to uphold academic integrity in the presence of generative models [8].

FRAMEWORK OVERVIEW

The framework is intentionally lightweight. Each component has two deliverables: (A) a one-page playbook for instructors and (B) a minimal dataset to observe change. Outcomes alignment yields a mapping table and a short list of assessable artifacts; policy yields course-level AI statements and a disclosure template; AI-enhanced teaching yields ready to use prompts and workflows; assessment design yields rubrics emphasizing process and oral defense; analytics yields a two-page dashboard with 6–8 indicators refreshed each term [1].

Implementation is iterative: choose two courses and one lab for a pilot; collect baseline metrics; then scale via communities of practice. The objective is not tool maximalism but dependable, auditable gains in learning and retention with integrity safeguards embedded by design. [8]

We propose a five-component framework that operates at the program-level: (1) outcomes alignment; (2) policy and ethics; (3) AI-enhanced teaching; (4) assessment design with process evidence; and (5) analytics for continuous improvement. Fig. 1 presents the architecture linking curriculum, policy, teaching, assessment, and analytics.

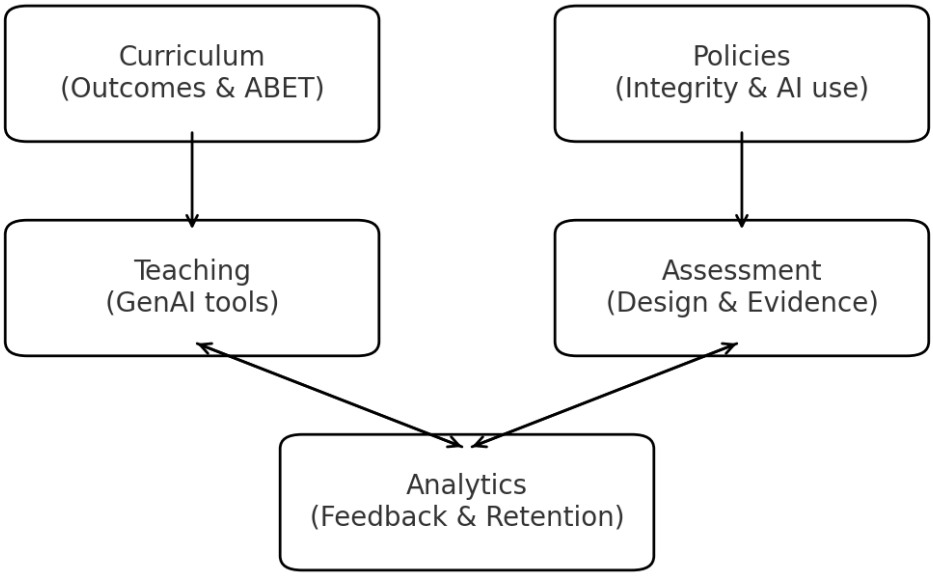


Fig. 1. *Program-level framework for AI integration in engineering education.*

OUTCOMES ALIGNMENT

For each course outcome, instructors specify the contribution of AI: ideation aid, scaffolding, or feedback generator. They also specify what remains strictly human-assessed (e.g., oral synthesis, troubleshooting under constraints). Performance indicators are phrased to make AI use observable: "documents alternative designs generated with and without AI, justifies selection via constraints," or "explains verification steps for AI-produced analyses" [9]. (see Table 1).

Table 1. *Example mapping of AI-enabled activities to ABET outcomes and assessable evidence. [9]*

ABET outcome (EAC 2025-2026, abridged)	AI-enabled activity	Evidence artifact
1. Solve complex engineering problems	AI-augmented ideation and trade-off analysis	Design log with prompt history & alternatives
3. Communicate effectively	AI-assisted drafting with self-explanations	Drafts with tracked changes + reflection
6. Experimentation	AI for data cleaning & exploratory analysis	Lab notebook, code, and validation plan
7. Acquire & apply new knowledge	AI-curated retrieval practice & reading plans	Practice logs and performance trend
Ethics & responsibility	Disclosure of AI use; model risk analysis	Signed AI use statement; error analysis

Alignment also encompasses equity: AI-generated scaffolds (worked examples, question prompts) are provided to lower the floor without lowering the ceiling. Students document use through a concise disclosure form incorporated into submissions. These artifacts feed assessment and analytics pipelines.

Programs should map AI-enabled activities to established student outcomes (e.g., ABET Criterion 3) such as problem solving, experimentation, communication, and ethical responsibilities. AI use should explicitly support, not replace, performance indicators tied to these outcomes [9].

Example mappings include: AI-augmented design ideation to broaden alternatives, AI-supported data analysis to improve rigor, and structured prompting for technical communication practice, each with human oversight.

POLICY AND ETHICS

Course AI statements include: (1) permitted uses by task type; (2) required disclosure format; (3) responsibilities for accuracy, privacy, and citation; and (4) consequences for misrepresentation. Because detector-only regimes are brittle, policies emphasize teachable integrity: students are assessed on how they used, verified, and learned from AI, not whether they avoided it entirely [8].

Ethics instruction is integrated into labs and projects (model limitations, bias, and error propagation). Students practice model risk analysis on their own prompts and produce short error-analysis notes demonstrating verification literacy. This cultivates habits aligned with professional codes and ABET expectations [9].

Departments should publish course-level AI use statements that specify permitted and prohibited uses, citation requirements, and accountability for errors. Policies should discourage over-reliance on automated detectors and emphasize teachable integrity—for example, by requiring disclosure of AI assistance and including reflective justification of prompts and revisions [8].

AI-ENHANCED TEACHING

Three patterns have proven classroom-ready: (i) Retrieval practice at scale—AI generates varied items aligned to outcomes; instructors vet seeds, then analytics schedule spacing; (ii) Draft and critique—students iterate with AI on reports or design memos while maintaining a change log; (iii) Coding and simulation hints—AI suggests tests and refactoring plans, with students validating and benchmarking performance [2].

To mitigate overreliance, instructors cap the proportion of AI-scaffolded work per assignment, require a reflection on the delta between initial and final understanding, and apply the rubric's verification dimension. Early adopters report time savings in feedback cycles that are reinvested into higher order coaching [1].

Instructors can combine generative AI with evidence-based strategies. Practical options include automated feedback on early drafts, hint generation for code and simulations, and AI-generated retrieval practice cards with spaced scheduling. These supports should be calibrated to avoid cognitive overload while keeping students in the loop [1]. (see Table 2)

***Table 2**. Assessment redesign tactics and the integrity risks they mitigate.*

Assessment tactic	Integrity risk mitigated	Implementation note
Oral defense/viva	Contract cheating; AI-only drafting	Short 5–10 min per team; rubric for conceptual grasp
Process portfolio (code/commit history)	Undeclared AI assistance; ghostwriting	Collect prompts, drafts, and diffs as evidence
In-lab practical with variable data	Answer sharing; memorized solutions	Randomize parameters; require reasoning steps
Studio critique/design review	Hallucinated claims; shallow understanding	Peer + instructor questions; require citations
Open-AI take-home with disclosure	Detector over-reliance; hidden use	Award marks for the quality of AI use and verification

ASSESSMENT DESIGN WITH INTEGRITY

We move from detection to design. Studio style reviews and vivas surface genuine understanding. Process portfolios preserve prompt histories, intermediate outputs, and decision rationales; graders evaluate reasoning, crosschecks, and improvements across versions. In lab practicals, use parametrized datasets or novel parts so that memorized or fully outsourced solutions confer little advantage [10].

Marking emphasizes verification: what authoritative sources were used; what unit checks, boundary tests, or sanity checks were performed; how disagreements between AI outputs and references were resolved. Where appropriate, students perform brief oral demonstrations (2–5 minutes) to defend choices under probing questions. [6]. See Table 3.

Table 3. *Rubric for evaluating AI-assisted coursework using process evidence.*

Dimension	Exceeds expectations	Meets expectations	Approaches expectations	Required evidence
Problem framing & ethics	Explicit risk analysis of AI use; citations/checks for claims	States allowed uses; acknowledges limitations	Vague policy compliance; misses key risks	AI use statement; prompt log
Method & iteration	Multiple prompt/draft iterations with justified changes	One iteration with a brief rationale	Minimal iteration; unclear rationale	Version history; diffs
Accuracy & verification	Triangulates outputs with authoritative sources and tests	Performs basic checks; a few sources	Little verification; relies on AI verbatim	Verification checklist; test results
Communication	Clear, well-structured technical writing with figures/tables	Understandable with minor issues	Disorganized; missing visuals	Final report; presentation
Academic integrity	Consistent process evidence; oral defense demonstrates mastery	Mostly consistent; can answer core questions	Gaps in process or defense; partial mastery	Oral defense notes; assessor rubric

Given the limitations of detection, assessment should be redesigned to make unauthorized outsourcing less beneficial and to value authentic performance. Tactics include oral defenses, studio critiques, process portfolios (with commit histories), and practical labs with variable data. Research and field reports indicate that AI-generated submissions can bypass current detectors, reinforcing a shift toward assessment-design strategies and even score well, underscoring the need for design-based integrity [6]. (see Table 4)

Table 4. *Program implementation roadmap with measurable KPIs*

Term	Key actions	Primary KPIs (targets)
Semester 1 (Pilot)	Adopt AI-supported retrieval practice in 2 core courses; publish course AI-use statements; staff training	Quiz to exam alignment ≥0.6; ++8–12 percentage-point retention gains on spaced items [6]; 100% disclosure compliance
Semester 2 (Scale)	Extend to labs; implement process portfolios & oral defenses; baseline outcome mapping to ABET [1]	Outcome attainment +5 pp; integrity incidents ≤ baseline; student satisfaction ≥ 4/5

Semester 3–4 (Institutionalize)	Governance for tool selection/privacy; annual review of outcomes; dashboarding & equity monitoring	DFW rate −10%; equity gap −5 pp; Replace reliance on detectors with design-based academic-integrity approaches (authentic tasks, process evidence, oral defenses) [7]

ANALYTICS FOR CONTINUOUS IMPROVEMENT

A minimal indicator set prevents data sprawl: (I) outcome attainment (rubric based); (II) item level retention on spaced materials; (III) integrity incidents (categorized by root cause); (IV) equity gaps by demographic proxy measures where permissible; (V) student experience (brief pulse); and (VI) workload (grading time) [1].
Triangulation matters: LMS traces alone are insufficient. We combine process artifacts (prompt logs, diffs), rubric scores, and small-n instructor notes each term to interpret anomalies and adjust scaffolds or policies. Dashboards show trends rather than league tables to support learning-oriented improvement. [1]
Programs should track a small set of indicators: course-level learning outcomes achievement, retention across terms, assessment integrity incidents, and equity gaps. Classroom analytics—from LMS logs to AI tool usage telemetry—can inform rapid cycles of improvement when triangulated with instructor judgment and student feedback [1].

IMPLEMENTATION ROADMAP

Pilot governance: the department nominates a lead, defines a change window (one term), selects courses, and allocates support (TA hours, consultation). Baselines are recorded for attainment, DFW, and integrity. Success is pre-registered as directional improvement against baselines, not absolute targets in the first term [1].
Scaling prioritizes coherence over coverage: materials and rubrics are templated; communities of practice share failures as well as wins. Procurement and privacy teams review tools for data handling; fallback plans are documented to avoid single vendor lock-in. [9]
Phase 1 (pilot): identify two core courses to pilot AI-enhanced retrieval practice and feedback. Establish disclosure policies and train staff on tool capabilities and limitations [8].
Phase 2 (scale): extend to lab courses with process portfolios and oral defenses; align mappings to program outcomes and collect baseline indicators [9].
Phase 3 (institutionalization): incorporate governance for tool selection, privacy, and data security; review outcome attainment annually; iterate on assessments and analytics dashboards [8]. (see Table 5)

Table 5. *Comparison of traditional and AI-integrated delivery across key dimensions.*

Dimension	Traditional Delivery	AI-Integrated Delivery
Learning Outcomes	Manual feedback, limited iterations	Automated feedback, rapid iteration, adaptive tasks
Retention	Cramming, low retrieval scheduling	Spaced retrieval, AI-curated practice
Academic Integrity	Proctoring-centric	Assessment redesign, process evidence, oral defense
Equity & Access	One-size-fits-all	Personalized scaffolding and supports
Workload	Instructor-heavy grading	AI-assisted grading with human moderation

To illustrate potential retention gains, Fig. 2 shows a simulated trajectory comparing a control condition with an AI-supported spaced retrieval approach, consistent with reported effects in STEM contexts [2].

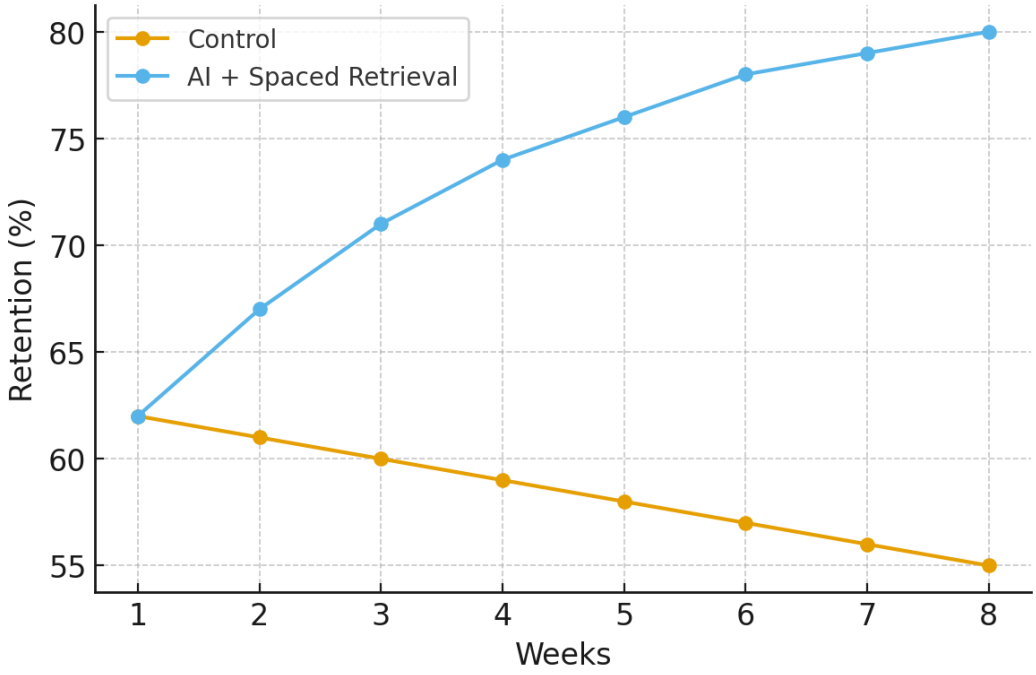


Fig. 2. *Illustrative retention gains with AI-supported spaced retrieval. [2]*

DISCUSSION

Our approach balances innovation with accountability. By tying AI use to specific outcomes and assessable artifacts, we avoid both lax permissiveness and inflexible prohibition. The primary risk is uneven instructor capacity; we mitigate via ready to adopt playbooks, shared banks of vetted prompts, and lightweight calibration sessions. [1]

Another risk is policy drift: without periodic review, allowances may expand without safeguards. Annual audits against ABET criteria and institutional policies ensure practices remain justifiable and student centred. The strongest evidence of success will be sustained improvements in retention on conceptually demanding topics with narrowing equity gaps [2].

The framework's novelty lies in its program-level alignment and assessment redesign grounded in integrity-by-design, rather than detection. While tooling evolves quickly, anchoring practices in established outcomes and learning science helps curricula that are resilient to rapid AI change [1].

Limitations include variability in tool performance across tasks and disciplines, staff capacity for change management, and the need to ensure accessibility. Early institutional pilots highlight both promise and risks, reinforcing the importance of governance and staff development [9].

CONCLUSION

Generative AI can be a leverage point for better learning, not a shortcut around it when embedded in outcomes, instruction, and assessment with integrity by design. The framework, instruments, and KPIs offered here are intentionally simple so that departments can execute quickly and iterate responsibly. Future work should test the framework in multi institution pilots and report comparative cost benefit and equity impacts using shared indicators [1]. Engineering programs can responsibly integrate generative AI by aligning

activities to outcomes, clarifying ethical use, redesigning assessment, and using analytics to improve learning and retention. The proposed framework offers a practical path to measurable gains while safeguarding academic integrity.
Additional implementation tables complement the framework and support adoption choices across courses. To operationalize the framework, the roadmap and rubric below provide concrete milestones, KPIs, and evaluation criteria.

REFERENCES

[1] U.S. Department of Education, Office of Educational Technology (2023). Artificial Intelligence and the Future of Teaching and Learning. URL: https://www.ed.gov/sites/ed/files/documents/ai-report/ai-report.pdf
[2] Bego, C. R., et al. (2024). Single-paper meta-analyses of the effects of spaced retrieval practice in STEM. International Journal of STEM Education.
[3] Wang, J., & Fan, W. (2025). The effect of ChatGPT on students' learning performance, learning perception, and higher-order thinking: insights from a meta-analysis. Humanities and Social Sciences Communications, 12, 621
[4] Deng, R., Jiang, M., Yu, X., Lu, Y., & Liu, S. (2025). Does ChatGPT enhance student learning? A systematic review and meta-analysis of experimental studies. Computers & Education, 227, 105224
[5] Baig, M. I., Yadegaridehkordi, E., et al. (2024). ChatGPT in higher education: A systematic literature review. Computers & Education: X
[6] Christianson, J. S. (2024). End the AI detection arms race. Patterns, 5(10), 101058
[7] Liang, P., et al. (2023). GPT detectors are biased against non-native English writers. Patterns. (PMCID: PMC10382961)
[8] UNESCO (2023, updated 2025). Guidance for generative AI in Education and Research. URL: https://unesdoc.unesco.org/ark:/48223/pf0000386693
[9] ABET. Criteria for Accrediting Engineering Programs, 2025–2026
[10] Jisc National Centre for AI (2024). Embracing generative AI in Assessments: A Guided Approach (Flowchart)
[11] JISC - Embracing GenerativeAI in Assessments:A Guided Approach. URL: https://nationalcentreforai.jiscinvolve.org/wp/files/2024/08/Embracing-Generative-AI-in-Assessments-Flowchart.pdf

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BRAILLE AS A PATH TO WRITTEN CONTENT

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Abstract: The aim of the paper is to describe the development, structure and practical application of Braille as a tactile writing system. By questioning the assumption that 90% of information is transmitted visually, the understanding of the importance of individual senses is re-examined. The article gives an overview of the history and the beginning of the development of Braille. The structure of modern Braille and the reading and writing processes are described. The historical overview gives an insight into the most important milestones from the early Latin relief scripts to the innovations of Louis Braille binary code with six dots, optimized for tactile reading and efficient writing. The article analyses the adaptations for different types of written content, including letters, numbers and musical notes, as well as auxiliary symbols and polysemic use to overcome the inherent limitations of the Braille cell. Modern aspects covered include reading techniques, average speeds and advances in Braille printing technology, electronic notebooks and adaptive digital devices that have greatly improved accessibility for blind users. The conclusion emphasizes the synergy between tactile and auditory technologies in development, with the goal of equal access to written information in education and daily life.
Key words: Braille, Braille alphabet, black print, reading, writing

INTRODUCTION

It is a common belief that we receive 90% of information through the sense of sight, [1]. This belief overlooks facts that senses often overlap. The data that makes up what we might roughly consider the same information is often received simultaneously through different senses. Therefore, depending on what we consider as information, it may very well be the case that, for example, we receive 90% of information through sight, 40% through hearing, another 15% through some other sense, etc. In that case, the claim that we receive 90% of information through sight says very little by itself. Available scientific sources state that our brains acquire about 90% of information from two senses only: sight (about 80%) and hearing (about 10%). The remaining 10% of information is distributed between smell, touch, and taste senses, [2]. The overlapping of the senses is confirmed by the fact that a blind person will not recount the plot of a typical film that is not overly visual but also not adapted for the blind significantly worse than a sighted person who watched the film without sound or subtitles—and in some cases, the blind person may even recount it better. Second, the brain supplements the data it receives based on prior knowledge. Such supplementation is very important for creating "coherent information." It is particularly significant in the case of hearing and smell, but by no means negligible in the case of vision, as various optical illusions confirm. For instance, a person who hears an insect (its flight, hopping, or chirping) can often fairly well identify which insect it is, even without seeing it. Conversely, a person who sees the insect may, due to optical effects, sometimes incorrectly conclude the species, or in extreme cases, mistake the insect for something that is not an insect, e.g., a twig. Third, vision is a directed sense, while hearing and smell, with certain qualifications, can be said to receive information from all directions. In the animal kingdom, for example, only fish have strict directional hearing and the localization of sound sources without moving the ear or head [3]. Fourth, there is the important question of how we measure the amount of information we receive. The amount of information a person receives is very difficult to measure objectively. This fact further diminishes the value of the claim made at the beginning of this paper. Moreover, if we take at face value the claim that we

receive 90% of information through sight, we might easily arrive at the inductive conclusion that it is nine times better to have good vision but lack all other senses combined than to lack only sight. Nevertheless, for completely blind people and people with very little residual vision—hereafter referred to briefly as the blind—the lack of vision significantly complicates life in many areas which negatively affect the overall quality of life, and to some extent the quality of social life as well. Various household tasks are much more accessible to the blind, although there are certain difficulties in this area as well.

There is yet another area that, especially today, is very important for quality of life but is not equally accessible to the blind as it is to the sighted: the use of written content. By the term "written content," we mean everything that we write down and read. This is primarily the written word, which, at least in Western culture, we usually encode with letters (as symbols largely corresponding to individual sounds), punctuation marks, and other auxiliary means. Another important type of written content is everything connected with numbers and arithmetic, usually encoded with digits and many auxiliary symbols regularly used in mathematics and natural sciences. A third important type of written content is recorded music, usually encoded with notes and numerous auxiliary symbols. In addition to these three main types of written content, there are also some peripheral ones, such as chemical reaction equations. In order to reduce, as much as possible, the difficulties that the blind face in various areas, various products and services exist. In this paper, we will focus on the Braille that reduce the inaccessibility of written content for the blind. The main aim of this paper is to familiarize the public with the methods by which blind people make use of written content.

BRAILLE RAISED SCRIPT

Prehistory and the Beginning of the Development of Braille

From the perspective of an inventor who is not also a user, the most intuitive way to make written content accessible to the blind is by relief representation of characters that are otherwise usually written in ink (hereafter, such non-relief characters will be referred to as black print). In other words, in such an adaptation no special script for the blind is used; rather, the script used by the sighted is presented in relief form and usually somewhat simplified—for example, only uppercase block letters are used, in a size that is easily accessible to the sense of touch.

There were several attempts at such adaptations, and here we mention some of the more significant ones. Valentin Haüy, [4] the founder of the Royal Institute for Blind Youth in Paris, used wooden letters and especially embossed letters pressed into paper in his teaching at the end of the 18th and the beginning of the 19th century. Letters made of copper wire were pressed into damp paper, leaving a trace in the form of raised relief lines. Paper thus inscribed could be bound into books. Haüy's adaptation was not particularly practical. The books were very bulky, and the relief wore out relatively quickly, becoming difficult to read. Finally, writing Haüy's letters was not simple, so only institutions could do it. In other words, Haüy's invention allowed blind people to read to some extent, but not to write in a script that they themselves could read.

Johann Wilhelm Klein, founder of the Institute for the Education of the Blind in Vienna, at the beginning of the 19th century devised a technique for producing Latin block letters not with solid lines like Haüy, but with dotted lines—lines made up of a dense sequence of raised (embossed) dots on paper. This technique was more practical than Haüy's—easier writing, greater durability of the text—but still not practical enough to take hold. Writing characters in Klein's technique was still relatively complicated, and besides, embossed reproduction of black print was too complex to be read quickly with the fingers.

Louis Braille, figure 1., in 1839 also devised a method of writing the Latin alphabet with raised dots: the so-called decapoint (French décapoint), [5]. At first, writing such letters was relatively complicated, but Braille's friend Pierre François Victor Foucault, with Braille's help, created in 1841 the raphigraph, a machine that greatly simplified the writing of decapoint. The specific feature of decapoint was that it was not conceived as a script for the blind (by then Braille

already existed), but as a means to facilitate written communication between the blind and the sighted. Namely, Braille had become completely blind at the age of five, and while at the Royal Institute for Blind Youth, he wanted to correspond with his parents and other sighted persons, which was impossible with Haüy's technology.



Fig. 1. *Louis Braille, source [4]*

William Moon, a blind teacher from Brighton (blind from the age of 21), in 1845 devised a specific, much-simplified embossed script of the Latin alphabet for the blind. For example, the letter a was two lines forming an upward-pointing angle; b was a vertical line with an arc on the lower right; c was a semicircle open to the right; d a semicircle open to the left; e a right angle (like a printed f without the middle horizontal stroke), etc. The simplified shapes were meant to contribute to easier reading. Similar to Braille, the first ten letters were also used to represent numbers. The script was bulky (taking up much more space than Braille), so there was also a kind of shorthand. This technique was probably the most practical for those who became blind later in life, like Moon himself. For a time it was relatively popular, but it was ultimately displaced by Braille.

The principle of embossed reproduction of black print was also used in the Optacon (short for optical to tactile converter), an electronic device that displayed characters in black print (on paper or on a monitor) in relief, i.e., as somewhat enlarged characters of identical shape, formed by tiny vibrating pins (at about 50 Hz). It consisted of a small camera with a guide that was moved across the surface with written content, and a converter with a small display approximately the size of the first two joints of the index finger, which was used to read the written content by touch. Optacons were manufactured from 1971 to 1996. They were expensive, reading with them was demanding, slow, and not particularly pleasant due to the pin vibration, so they never gained widespread use. Still, in the 1970s and 1980s, and to some extent in the 1990s, the Optacon was the only tool by which a blind person could independently read black print.

At the end of this brief overview, it should be emphasized that the reproduction of black print is yet another piece of evidence showing that what is most intuitive from the inventor's perspective is not always the best for the user.

A revolutionary step towards Braille was taken by Nicolas-Charles-Marie Barbier de La Serre. Already during Haüy's directorship, Barbier sent his invention to the Royal Institute for Blind Youth: a dotted script that did not reproduce the shapes of black print characters. Haüy was not interested in the script because the institute used embossed reproduction of black print according to his own already described technology. After Haüy's death, Barbier presented his invention to the new director, and this time he received support. Barbier's script at first glance is relatively similar to Braille. One cell, i.e., one character space, contained twelve positions, i.e., up to twelve dots: six dots in two columns. In such a system it was possible to obtain 4,096 (2^{12}) characters, from the character without any dot (space), through various combinations with different numbers of dots, to the character consisting of all twelve dots. In such a multitude of

characters it was certainly impossible to find one's way, nor was such a number of characters necessary. Therefore, Barbier devised three systems with a relatively small number of characters: a system of 25, a system of 30, and a system of 36 characters.

Barbier chose the characters that would enter his systems by using tables of 5×5, 5×6 (i.e., 5 rows and 6 columns), and 6×6 cells. The coordinates of each cell in the table defined a character in such a way that the row number of the table indicated the number of dots in the first column of the character cell, arranged in a continuous sequence from the top of the column downward, while the column number of the table indicated the number of dots in the second column of the character cell, also arranged in a continuous sequence from the top downward. Thus, the letter numerically marked by Barbier as 1,1 (the letter a) consisted of the two topmost dots of the character cell. The dots in the character marked as 5,5 (the letter Z) occupied ten of the twelve positions in the character cell, i.e., all except the two lowest. The character marked as 4,2 (the letter q) had the four topmost dots in the first column and the two topmost dots in the second column.

Barbier's script had certain advantages over Haüy's embossed reproduction of black print: the characters were more durable, they were easier to read, and most importantly, they were relatively simple to write. Writing in Barbier's script used tools that blind people could handle without difficulty. Writing was done with a stylus and equipment similar to the so-called slate. Barbier's script also had some easily removable shortcomings: the character cell was too tall, and individual characters contained too many dots (both slowed down reading), while at the same time the number of available characters was too small.

Louis Braille noticed these shortcomings. Unlike Haüy, Klein, and Barbier, Braille was himself blind, so he approached the problem from the perspective of the user. Braille was a student at the Royal Institute for Blind Youth, and later worked there as a teacher.

He devised the first version of Braille in 1824, at only fifteen years of age, and published it in 1829, Figure 2. The main specific feature of the first version of Braille, compared both with the later, modern version published in 1837 and with Barbier's script, was that the components of the characters could be both dots and horizontal dashes. The character cell in the first version of Braille, if we look only at the dots, had six positions, just as in the second version. In other words, up to six dots could be arranged in two columns of three dots each. The dots were counted from top to bottom, first in the left column and then in the right, i.e., dots 1, 2, and 3 were in the left column from top to bottom, and dots 4, 5, and 6 were in the right column. In addition, the place of two horizontally adjacent dots—dots 1 and 4, 2 and 5, or 3 and 6—could also be occupied by a horizontal dash. Horizontal dashes could appear in three positions, which are marked with underlined numbers from top to bottom as 1, 2, and 3. In this way the system could have at most 125 different characters, including the space. Of these 125 characters, Braille catalogued only 90, which he divided into nine decades, i.e., nine groups of ten characters each. However, even among these 90 catalogued characters, he left several without assigned value.



Fig. 2. *Braille's original code, 1856, source [5]*

The first four decades consisted only of dots, and in form and content they basically corresponded to the characters of modern Braille. These characters primarily denoted letters. The fifth decade denoted the digits 1, 2, 3, 4, 5, 6, 7, 8, 9, and 0, and looked like this:
1, 12, 12, 125, 15, 12, 142, 42, 4, 45.
The sixth decade contained punctuation marks and was obtained by adding dash 3 to the characters of the first decade. The seventh decade denoted mathematical symbols and notes. It was formed by moving the characters of the first decade to the bottom of the cell, with dash 1 placed at the top of the cell: for example, 13, 123, 136, 1256, etc. Part of the eighth decade also represented mathematical symbols, while part had no assigned value. All characters of the eighth decade contained dash 2, and they were obtained from the seventh decade by switching the positions of the upper dash and the middle dots: for example, 23, 123, 236, 1246, etc. In the ninth decade, only the first three characters had the value of auxiliary signs, while the rest had no assigned value. They were obtained from the fifth decade by adding dash 3.
Such a system had certain advantages over Barbier's. The main advantage was that Braille's characters were of an optimal size for reading with the fingertip, whereas Barbier's were too large. In this respect, Braille's system proved only partly redundant, since about thirty characters had no value. By contrast, the number of possible characters in Barbier's system greatly exceeded the number needed, while in practice too few characters were actually used—significantly fewer than in Braille's system.
Still, the first version of Braille had certain shortcomings. It turned out that during faster reading the dashes were difficult to distinguish from the dots. Moreover, dots and dashes were certainly harder to write than dots alone. In this sense Braille's ternary code was actually a step backward compared to Barbier's binary code. True, such a ternary code allowed for more characters than a six-digit binary code, but after a few years Braille realized that the future lay in binary code, and that the insufficient number of characters would have to be compensated for in other ways.
The second version of Braille is, generally speaking, the best writing system for the blind to date. The characters are of optimal size for fingertip reading. They consist exclusively of dots. The fact that the characters consist only of dots, and of a relatively small number of dots, simplifies writing, whether with the slate and stylus (adapted from Barbier's writing tools), the Braille typewriter, or its modern equivalents. The same fact also allows for relatively fast reading. Braille characters form very simple letter shapes that the fingertip quickly recognizes. A Braille character is perceived primarily as a simple dotted shape: the reader does not focus on each dot separately and does not need, as in the first version, to concentrate on distinguishing between dots and dashes.
The number of characters is relatively large (greater than the number used in Barbier's systems), and the insufficient number of symbols is compensated for through polysemy of individual characters and combinations of characters.

Modern Braille as a System

Classical modern Braille (six-dot Braille) is a six-digit binary code designed for the blind, in which a raised dot corresponds to the value 1, and the absence of a dot corresponds to 0, figure 3. Braille characters encode letters, numbers, musical notes, various auxiliary symbols (punctuation, mathematical symbols, auxiliary signs in music notation), as well as abbreviations, symbols, and more. In this sense, although Braille is usually considered a script, it is not actually a typical script, since scripts are usually limited to the written word and, in some cases, to the specific notation of numbers. Braille is rather a relief code that makes written content accessible to the blind. As a six-digit binary code, classical Braille has only 64 (i.e., 2^6) single-cell characters, including the space. In the original second version of Braille, these characters were organized into sequences. There are six sequences of ten characters each, and one sequence of four characters. The corresponding system of sequences is essentially valid for all Braille systems in which the coding is close to that of the second version.

These are the systems predominantly used by the blind in Europe and America, as well as many others.

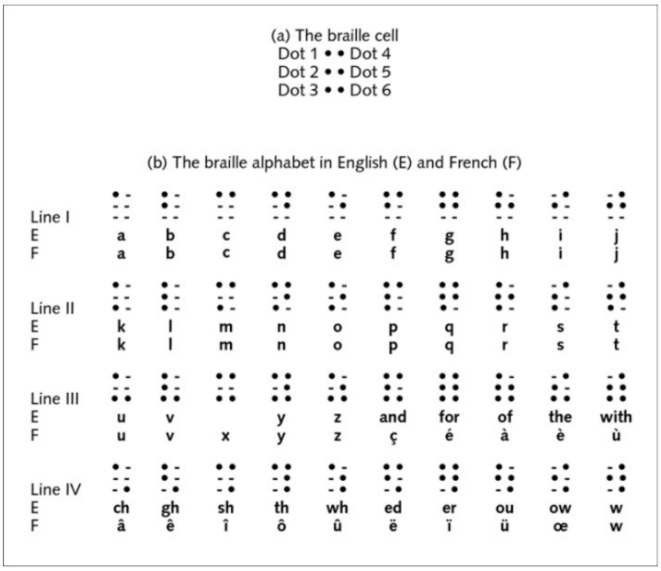


Fig. 3. *The Braille alphabet in english and french, source [6]*

The dots in a Braille cell, as stated earlier, are arranged in two columns of three dots each, and are counted from top to bottom: first in the left column (1, 2, 3) and then in the right (4, 5, 6).
The first four sequences essentially encompass the French alphabet, so that the letters with diacritics are placed at the end of the list, and the last letter in the fourth sequence is w, which is visible in Figure 3. The Braille alphabet in English and French, [6].
The characters of the first sequence correspond to the letters a, b, c, d, e, f, g, h, i, j. However, these same characters also denote the numbers 1, 2, 3, 4, 5, 6, 7, 8, 9, 0 if preceded (not each digit individually) by the number sign (3456). The letters from d (145) to j (245) also denote quaver (eighth) notes.
The second sequence corresponds to the letters k, l, m, n, o, p, q, r, s, t. The fourth through tenth characters of this sequence (letters n to t) also denote half notes.
The third sequence corresponds to the letters u, v, x, y, z, plus five French letters with diacritics. However, the fourth character (y) through the last in the sequence also denote whole notes: C, D, E, F, G, A, B.
The first nine characters of the fourth sequence generally denote various letters with diacritics, digraph abbreviations, and the like, while the tenth character is w. The fourth through tenth characters also denote quarter notes. In other words, a half note is derived from a whole note by subtracting dot 6, a quarter note by subtracting dot 3, and an eighth note by subtracting dots 3 and 6 from the whole note. Sixteenth notes are written as whole notes, and thirty-second notes as half notes.

Reading and Writing Modern Braille

When reading Braille, the reader usually glides both hands across the embossed surface. The main role in reading is played by the index finger of one hand, while the other fingers mostly help in tracking the lines and only slightly in recognizing the characters. The preference for the left or right index finger in reading does not strictly correlate with left- or right-handedness. Some right-handed people read primarily with the left index finger, others with the right. Braille can be read relatively well with only the hand that plays the primary role. Reading exclusively with the hand that plays a secondary role, however, is significantly more difficult. There are, to be sure, certain ambidextrous Braille readers. The question remains whether such ambidexterity can be acquired through training.

The average reading speed of Braille in Croatian is 60 to 80 words per minute. The index finger does not follow the text at a constant speed, but moves more quickly over more predictable parts of the text, and more slowly over less predictable parts, where it may also pause or, if necessary, move back. Since Braille is basically read with one finger, the reader cannot perceive the content of a larger section of text at once. The skin contains receptors for warmth, cold, touch, and pain. All more or less successful attempts to bring written content closer to the blind through the skin are based precisely on the sense of touch. Clearly, it would never occur to a normal person to bring written content closer to the blind through the sense of pain. But what about warmth and cold? A new idea has emerged at the Faculty of Electrical Engineering, Computer Science and Information Technology Osijek to explore the possibilities of making a Braille display based on long-wave infrared radiation. Approach represents a new technical solution that proposes the use of passive elements positioned in a six-dot Braille grid instead of actuators. The above solution requires fewer resources, reduces investment costs and provides the opportunity to expand the use of Braille. During the implementation of the project "Braille display screen based on long-wave infrared radiation" NPOO.C3.2.R3-I1.05.0191 preliminary research have shown that the senses of warmth presents a challenge for reading, most likely for two reasons, [7]. On the one hand, the fingertips, which are most suitable for following text, are not particularly sensitive to small temperature differences which could be detected on the first prototype. On the other hand, the human reaction to temperature changes is relatively slow and cannot perceive the ten or so tiny changes per second that the sense of touch perceives when reading Braille.

Today, in printing houses—and partly also for private use—we employ Braille printers. In the Braille printing house of the Croatian Blind Union, printers have been in use since the 1990s. Some printers print only single-sided, but nowadays double-sided printers are generally used. Many printers still use continuous feed paper with guiding holes, but printers that use cut-sheet paper are more highly valued.

Braille printers are generally much larger, much slower, much louder, and of course, much more expensive than black-print printers. Their speed varies, but more common speeds are 140, 300, and 330 characters per second. Braille printers have certainly made a major contribution to the speed of book production and, more broadly, to the availability of written content for the blind. Braille can also be written with some electronic devices. Electric Braille typewriters are rare. Much more common today are so-called electronic notetakers: relatively compact electronic devices with a six-dot or eight-dot Braille keyboard as the input module, and speech, a Braille display (usually 18 or 40 cells), or both as the output module. For reading purposes there are braille lines and screens, although screens are much less accessible. Braille can also be written with some electronic devices. Electric Braille typewriters are rare. Much more common today are so-called electronic notetakers: relatively compact electronic devices with a six-dot or eight-dot Braille keyboard as the input module, and speech, a Braille display (usually 18 or 40 cells), or both as the output module.

Electronic notetakers have their own memory and the ability to export data, and more recently they can also hold memory cards. Simpler notetakers store data as files in txt format. Notetakers with a Braille display (module) can be connected to a computer and used as a Braille display (device).

Electronic notetakers often have additional functions such as a clock, alarm, stopwatch, timer, calendar, calculator, etc. Some notetakers are small computers in their own right and can connect to the Internet. We believe that an electronic notetaker is not a good replacement for a computer, but it can be an excellent supplement to one. This is especially true of simpler notetakers, which respond quickly and conserve rechargeable batteries.

They are useful as a tool for taking lecture notes: unlike Braille typewriters, they are light, compact, and quiet, and the text created with a notetaker can easily be retrieved in various formats. They are excellent as notebooks for all kinds of notes, as a book—or rather, a whole library of books and other texts—that one can carry around, and so on. Some notetakers store text automatically as it is entered, while with others the text must be saved before switching the device off (as with documents on a computer). Automatic saving during input is by far the

better option, since a user can easily forget to save and, upon switching the device off, lose everything written. As might be expected, electronic notetakers are also very expensive.
Finally, even a smartphone adapted for the blind can have a virtual Braille keyboard as the input module. The user enters data by "writing" on the screen in a way similar to typing on a real Braille keyboard. In this case, as to some extent also with electronic notetakers, we are no longer dealing with the writing of Braille itself, but with the writing of digital text using the method originally designed for Braille entry.

CONCLUSION

In this paper, we have tried to present Braille as intermediary of written content for the blind to the general public, hoping that this topic might be of interest to those who do not know much about it. Naturally, we have also aimed for the information provided here to be not only interesting but also useful, especially to those who work with or intend to work with assistive technologies for the blind. The most important thing we wished to emphasize—because, despite being self-evident, it is sometimes overlooked—is that potential users usually know best what they need. In this regard, it is desirable: that scientists and manufacturers of assistive technologies consult with potential users when designing and implementing projects; those actual users of finished products are given the opportunity to suggest how those products could be improved. When it comes to providing access to written content for the blind, those less familiar with the field often have in mind only one of the two basic methods—or predominantly one: often Braille, as the older method specifically tied to the blind, even though speech is probably the more important means today. In this paper, we have presented written Braille in an abbreviated form. Due to the limited scope of the paper, many details related to the adaptation of written content for the blind could not even be mentioned, let alone described in more detail.

REFERENCES

[1] Wikipedia, Human eye, https://hr.wikipedia.org/wiki/Ljudsko_oko, accessed 30.04.2025.
[2] Man, D., Olchawa, R. (2018). Brain Biophysics: Perception, Consciousness, Creativity. Brain Computer Interface (BCI). In: Hunek, W., Paszkiel, S. (eds) Biomedical Engineering and Neuroscience. BCI 2018. Advances in Intelligent Systems and Computing, vol 720. Springer, Cham. https://doi.org/10.1007/978-3-319-75025-5_5
[3] Sisneros, J.A., Rogers, P.H. (2016). Directional Hearing and Sound Source Localization in Fishes. In: Sisneros, J. (eds) Fish Hearing and Bioacoustics. Advances in Experimental Medicine and Biology, vol 877. Springer, Cham. https://doi.org/10.1007/978-3-319-21059-9_7
[4] Yvette Hatwell, Édouard Gentaz, Origine et évolution des recherches psychologiques sur le toucher en France, L'Année psychologique 2011/4 Vol. 111, Pages 701-723, 2017, https://doi.org/10.3917/anpsy.114.0701
[5] Javier Jiménez, Jesús Olea,Jesús Torres,Inmaculada Alonso, Dirk Harder, Konstanze Fischer, Biography of Louis Braille and Invention of the Braille Alphabet, Survey of Ophthalmology, Volume 54, Issue 1, January–February 2009, Pages 142-149, https://doi.org/10.1016/j.survophthal.2008.10.006
[6] Hatwell, Y., Gentaz, E. (2008). Early psychological studies on touch in France. In: Grunwald, M. (eds) Human Haptic Perception: Basics and Applications. Birkhäuser Basel. https://doi.org/10.1007/978-3-7643-7612-3_4
[7] FERIT, Preliminary research on the project NPOO.C3.2.R3-I1.05.0191 "Braille display screen based on long-wave infrared radiation", Osijek 2025.

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EXPERIMENTAL INVESTIGATION OF THE IMPACT TOUGHNESS OF POLYLACTIC ACID- PLA SPECIMENS FABRICATED BY FFF 3D PRINTING USING THE CHARPY METHOD

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Abstract: This paper presents an experimental investigation of the impact toughness of 3D-printed specimens made of polylactic acid (PLA) using the Fused Filament Fabrication (FFF) process, tested by the Charpy method. One of the main disadvantages of 3D printing is that the parts often have significantly lower mechanical properties, making mechanical testing necessary to determine their functional suitability. The testing of impact toughness for plastic materials was carried out in accordance with the standard EN ISO 179-1: 2023 Plastics- Determination of Charpy impact properties- Part 1: Non-instrumented impact test. Among the most important adjustable 3D printing parameters in the FFF process are the layer height and infill pattern. This research specifically investigates how different layer heights and infill types (linear, zig-zag, and concentric) affect the impact toughness of PLA specimens. The results confirm that higher layer heights and concentric infill patterns result in greater impact toughness, due to better interlayer bonding and more effective stress distribution under impact load.
Key words: Impact toughness testing, Charpy method, Additive manufacturing, Fused Filament Fabrication (FFF), Polylactic acid (PLA).

INTRODUCTION

Parts produced by 3D printing exhibit weaker mechanical properties and lower surface finish quality, which makes it necessary to determine their mechanical characteristics: toughness, hardness, tensile strength, as well as impact strength, compressive strength, flexural strength, and fatigue strength. Additionally, it is important to assess creep, aging, coefficient of friction, shear resistance, and crack propagation resistance in accordance with EN ISO 17296-3: Additive manufacturing – General principles – Part 3: Main characteristics and corresponding test methods.
This standard also defines categories of testing for metal, plastic, and ceramic parts, grouping them into three categories: group H: Testing of functional parts that are highly safety-critical, group M: Testing of functional parts that are not safety-critical, and group L: Testing of parts during the design phase or prototype parts [1].
The testing of toughness for plastic materials is defined by the EN ISO 179-1 standard: Plastics – Determination of Charpy impact properties – Part 1: Non-instrumented impact [2].
Previous research has shown that the impact energy of PLA specimens without notches produced by the FFF 3D printing process is 0.55 J. In that case, the layer orientation angle relative to the direction of applied force during testing was between 15° and 75°, while for layer angles between 30° and 60°, the impact energy was 0.54 J [3].
Similar results were found in a study where the Charpy impact strength of PLA specimens produced by 3D printing was 5 kJ/m², which is equivalent to a impact energy of 0.2 J [4].
On the other hand, research using carbon fiber reinforced PLA-CF with a 15% carbon fiber content, which provides high stiffness and bending resistance, showed that the toughness of PLA specimens produced via the FFF method significantly increases, reaching values of 13,4 kJ/m², 14 kJ/m², and 16,5 kJ/m² [5, 6, 7].
The aim of this study is to determine the impact toughness of PLA plastic specimens using the Charpy method, depending on the layer height in the shell and infill. Additionally, it is necessary to determine the toughness for different infill patterns (linear, zig-zag, and concentric) at the same layer height.

The research hypotheses are that the highest impact toughness of PLA plastic specimens is achieved at the highest layer height in both the shell and the infill, and that the impact toughness differs for various infill patterns, even at the same layer height.

ADDITIVE MANUFACTURING

Additive manufacturing can be divided according to ISO 17296-2: Additive technologies- General principles- Part 2: Overview of process categories and filling, into: Vat photopolymerization- laser stereolithography (SLA) and full-layer illumination-based stereolithography (DLP-SLA, LCD-SLA); Material extrusion (FFF- Fused filament fabrication); Binder jetting; Material jetting; Powder bed fusion- procedures using laser (SLS, SLM, DMLS) and procedures using electron beam (EBM); Directed energy deposition (DED- Deposition of materials using directed energy) and Sheet lamination (LOM- Laminated object manufacturing, PSL) [8].
The material extrusion process (FFF – Fused Filament Fabrication or FDM – Fused Deposition Modeling, the trademark of the company Stratasys) uses a solid thermoplastic material – filament – which is pushed through a heated nozzle. The temperature of the nozzle depends on the type of polymer, and the material is deposited in a molten or semi-molten state onto a heated or unheated build platform. After deposition, the material solidifies and forms the desired part layer by layer [9].
The most important adjustable parameters in the FFF (Fused Filament Fabrication) 3D printing process include: print speed, extrusion speed, layer height in the shell and infill, nozzle temperature, and build plate temperature.
The main limitations of the material extrusion process are related to the anisotropic nature of the printed parts. Layer-by-layer extrusion results in parts that are inherently weaker in one direction. The orientation of the part during the printing process significantly affects its strength in each direction. Infill percentage also impacts the part's strength. Most parts and prototypes produced by 3D printing have around 20% infill, which greatly reduces production cost and time. However, in areas where structural strength is required, 100% infill is used, which increases both the time and cost of fabrication [10].

POLYLACTIC ACID (PLA)

There is a wide variety of polymers with different mechanical, physical, chemical, electrical, thermal, and other properties, which makes them suitable for a broad range of applications.
PLA (Polylactic Acid) is a thermoplastic, biodegradable plastic derived from organic sources (such as corn starch, sugarcane, or sugar beet) – produced through fermentation of plant starch. It has similar properties to polypropylene (PP), polyethylene (PE), or polystyrene (PS). It is commonly used for manufacturing food containers, films, and medical implants, and it has a high surface energy, making it ideal for 3D printing.
The main disadvantages of PLA are its low heat resistance and relatively low strength. The properties of PLA are shown in Table 1 [11].

Table 1. *Properties of Polylactic Acid (PLA)*

The parameters	Values
Heat Deflection Temparature, EN ISO 75	52 °C
Density	1,24 g/cm³
Tensile Strength, EN ISO 527-1	50 MPa
Bend Strength, EN ISO 178	80 MPa
Impact Toughness IZOD Method, EN ISO 180	96,1 (J/m)
Shrinkage rates	0,37-0,41%

The chemical formula of polylactic acid (PLA) is H-[OCH(CH_3)CO]$_n$-OH, and the PLA polymer used for this type of 3D printing is in the form of a filament.

EXPERIMENT

The test specimens were produced using the FFF method on a Creality Ender 5 Pro 3D printer with Creality PLA polymer filament, 1.75 mm in diameter. The properties of the Creality PLA filament are shown in Table 2.

Table 2. *Properties of Creality PLA Filament*

The parameters	Values
Filament type	CR PLA black
Diameter (mm)	1,75
Melting point (°C)	190-210
Build plate temperature (°C)	0-60
Tensile Strength	≥60MPa

The 3D printing parameters were as follows: extrusion speed of 80 mm/s, layer heights of 0.1 mm and 0.2 mm in both the shell and infill, nozzle temperature of 200 °C, build plate temperature of 60 °C, and 100% infill. The Creality Ender 5 Pro 3D printer used for the fabrication is shown in Figure 1 [12].



Fig. 1. *3D printer Creality 5 pro*

The technical specifications of the Creality Ender 5 Pro 3D printer are shown in Table 3.

Table 3. *Creality 5 Pro 3D Printer Technical Features*

The parameters	Values
Materials	PLA, ABS, PETG, TPU
Max. part dimensions (mm)	300 x 225 x 380
Filament diameter (mm)	1.75
Nozzle outlet diameter (mm)	0.4
Working temperature (°C)	300
Build plate temperature (°C)	110

Charpy impact toughness testing was performed on notched specimens, type A1, produced using the FFF (Fused Filament Fabrication) 3D printing process with polylactic acid (PLA) polymer filament.
The specimen shape and dimensions were defined according to the EN ISO 179-1:2023 standard: Plastics – Determination of Charpy impact properties – Part 1: Non-instrumented impact test, and are shown in Figure 2.
The layers were oriented in such a way that, when observing the impact direction relative to the laminate plane, the impact was applied parallel- edgewise.

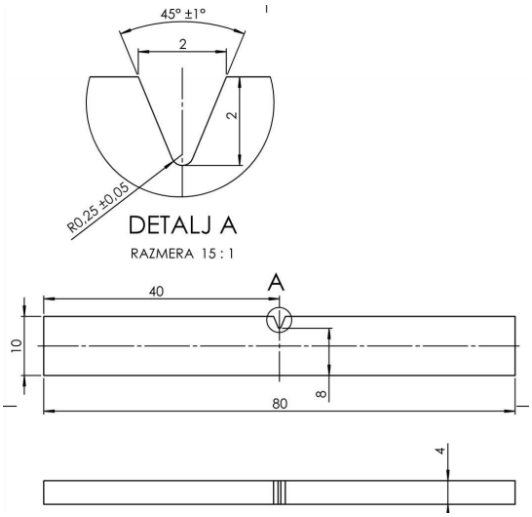


Fig 2. *Notched specimen*

The 3D CAD model of the specimen for Charpy impact toughness testing is shown in Figure 3.

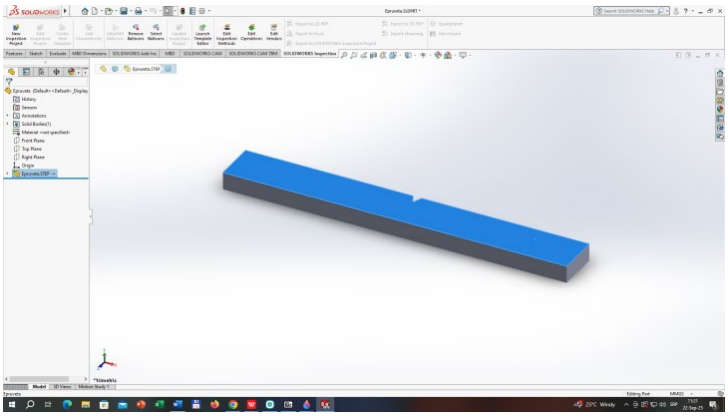


Fig. 3. *3D CAD model*

The STL file of the specimen for Charpy impact toughness testing is shown in Figure 4.

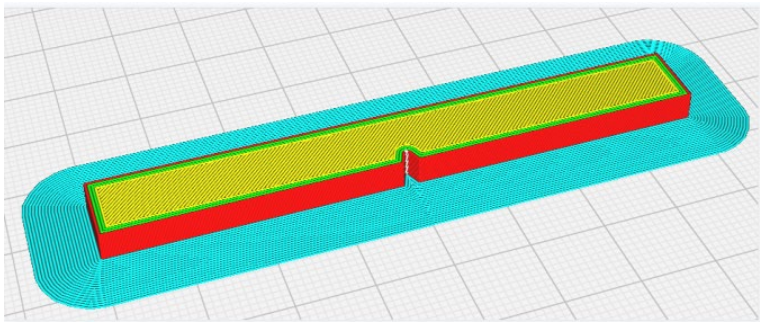


Fig.4. *The STL file*

The appearance of the specimens for Charpy impact toughness testing is shown in Figure 5. Specimen No. 1: PLA specimen with 100% zig-zag infill and 0.1 mm layer height. Specimen No. 2: PLA specimen with 100% concentric infill and 0.1 mm layer height. Specimen No. 3: PLA specimen with 100% linear infill and 0.2 mm layer height. Specimen No. 4: PLA specimen with 100% linear infill and 0.1 mm layer height.



Fig. 5. *The appearance of the specimens*

A Charpy impact testing device was used as the measuring instrument for determining impact toughness (Figure 6). Orientation of the samples: flat on the mat and in a horizontal position.

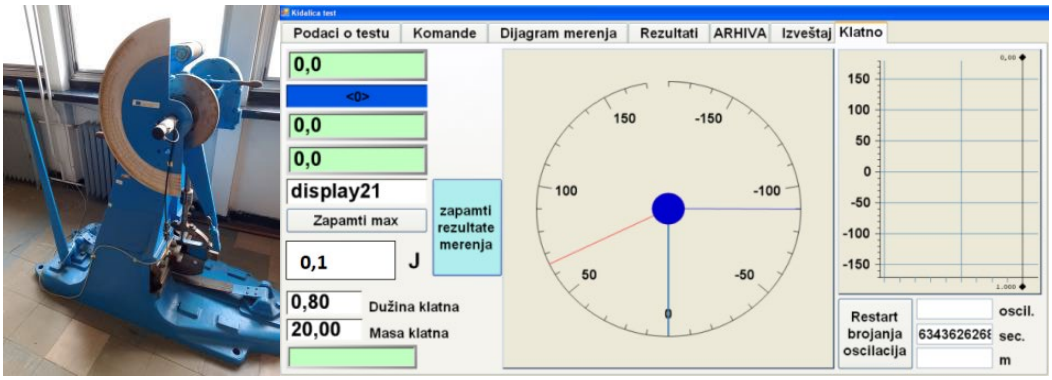


Fig.6*. Measurement of Impact Toughness of PLA Specimens*

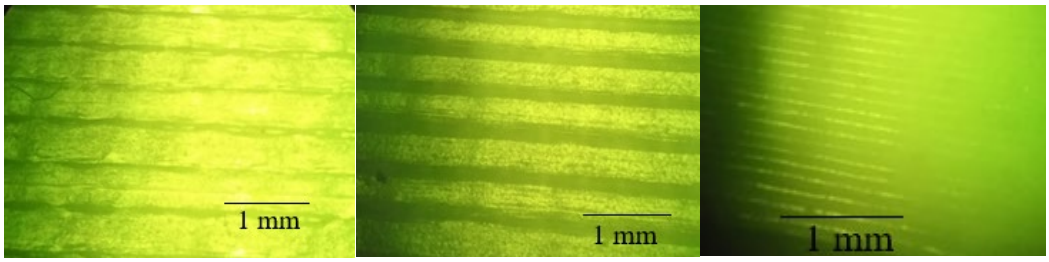
RESEARCH RESULTS

The surface quality of a workpiece made of PLA plastic depends on the layer height applied in the shell and infill. The lower the layer height, the higher the surface quality and greater the ability to produce fine details however, the printing time increases linearly.
The values of Impact energy and Charpy impact strength of notched specimens for different infill patterns and layer heights are presented in Table 4.

Table 4. *Values of Impact Energy and Charpy Impact Strength for Different infill patterns and layer heights*

Pattern	Build plate temerature (°C)	Layer height (mm)	Impact energy- W (J)	Charpy impact strength- a_{cN} (kJ/m^2)
Zig Zag	60	0,1	0,1	3,13
Concentric			0,2	6,25
Lines			0,1	3,13
Lines		0,2	0,2	6,25

Microscopic images of PLA specimens with layer heights of 100 and 200 microns, at 5x magnification, along with a cross-sectional view of the 4 mm thick layers, are shown in Figure 7.



a) b) c)

***Fig. 7**. Microscopic images of PLA samples with a) layer heights of 100, b) layer heights of 200 microns at 5x magnification and c) a cross-section of layers with a layer height of 100 microns.*

In Figure 7, the darker lines represent the grooves between the layers, which are locations of stress concentration. The wider these grooves, the rougher the surface. Microscopic examination revealed that the layer width is greatest at the highest applied layer height.
Figure 7c shows the cross-section of the specimen and the number of layers for a layer height of 0.1 mm.
The Charpy impact strength of PLA samples produced by FFF 3D printing technology depends on the layer height, being higher for larger layer heights. The Impact energy is 0.2 J for a layer height of 0.2 mm and 0.1 J for a layer height of 0.1 mm.

CONCLUSION

3D printing using the FFF material extrusion method results in low surface quality. From the standpoint of impact toughness, the hypothesis was confirmed that the highest impact toughness of PLA specimens is achieved with a larger layer height of 0.2 mm at full infill in both the shell and infill. The impact toughness is twice as low for half the layer thickness when using linear infill. This is because a greater layer height reduces the number of layers in the specimen, leading to better interlayer bonding and fewer sites for crack initiation, thereby increasing impact resistance.
The second hypothesis was also confirmed: impact toughness varies depending on the infill pattern, with all other parameters and layer height kept constant. It is twice as high with concentric infill, which better distributes stress during impact, compared to linear and zig-zag infills, which have more fractures at joints, reducing overall toughness.
These results highlight the importance of optimizing FDM printing parameters to improve the mechanical properties of finished products.

REFERENCE

[1] EN ISO 17296-3: Additive manufacturing - General principles - Part 3: Main characteristics and corresponding test methods.
[2] EN ISO 179-1: Plastics- Determination of Charpy impact properties - Part 1: Non-instrumented impact.
[3] Erdaş, M. U., Yıldız, B. S., Yıldız, A. R.: Experimental analysis of the effects of different production directions on the mechanical characteristics of ABS, PLA, and PETG materials produced by FDM, Testing for Welding, Joining or Additive Manufacturing Applications, January 9, 2024. DOI:10.1515/mt-2023-0206
[4] Gómez Amador, A. M., Venturini Avendano, R. A., González, A. Q., Fernández, L. P.: Mechanical characterization and testing of multi-polymer combinations in 3D printing, Heliyon, Jan 31;11(3):e42420, 2025. DOI: 10.1016/j.heliyon.2025.e42420
[5] Internet source: https://www.in3dtec.com/how-to-choose-the-right-3d-printing-material/?utm, Retrieved 2025-20-09.
[6] Internet source: https://craftfac.com/materials/3d-printing-plastics/?utm, Retrieved 2025-20-09.

[7] Sedlak, J., Joska, Z., Jansky, J., Zouhar, J., Kolomy, S., Slany, M., Svasta, A., Jirousek, J.: Analysis of the Mechanical Properties of 3D-Printed Plastic Samples Subjected to Selected Degradation Effects, Materials (Basel).16(8):3268, Apr 21, 2023. doi.org/10.3390/ma16083268
[8] EN ISO 17296-2: Additive manufacturing - General principles - Part 2: Overview of process categories and feedstock.
[9] Internet source: https://www.stratasys.com/en/fdm-systems, Retrieved 2025-09-05.
[10] Redwood, B, Schöffer, F., Garret, B.: The 3D printing handbook: Technologies, Design and Applications, 3D Hubs, 2017.
[11] Internet source: https://www.twi-global.com/technical-knowledge/faqs/what-is-pla, Retrieved 2025-10-09.
[12] Internet source: https://www.creality.com/products/creality-cr-5-pro-h-3d-printer. Retrieved 2025-06-06.

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STRESS ANALYSIS OF WELDED JOINT BEHAVIOR UNDER TENSILE LOADING USING FEM

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Abstract: The strength assessment of welded joints can be carried out through traditional analytical approaches or by employing the finite element method (FEM). This paper presents the modeling process of a butt-welded joint using SolidWorks Simulation software, along with an analysis of its behavior under load. Prior to the simulation, the tensile strength of a butt-welded aluminum specimen (Al 99.5) was experimentally determined. Since fractures occurred in the base material rather than in the weld, the simulation utilized material properties from the SolidWorks database corresponding to the base metal. The findings obtained through both experimental testing and numerical simulation offer practical insights and guidelines for evaluating the strength of welded joints.
Keywords: welded joints, structural strength, butt weld, finite element analysis, SolidWorks Simulation

INTRODUCTION

Welding is one of the main manufacturing processes used for assembling metallic and some non-metallic materials. In the welding process, high temperature differences result in significant thermal stresses, which affect the distribution of residual stresses in structural components.The significant time consumption and high costs of conducting experiments to determine the optimal parameters of the manufacturing process serve as a motivation to include the use of software simulations in component design, as well as in their production, which enables the optimization of the manufacturing process. The implementation of microstructural effects that develop during welding into simulation software represents a major advancement in such simulations. Computational welding mechanics is a modeling process used to predict the thermal, mechanical, and structural properties of materials affected by the welding process [1].
Welded joints can be analyzed using classical analysis or Finite Element Method (FEM). Finite element analysis (FEA) quite accurately identifies the load path, which can be difficult using classical analysis in the case of complex structures [7].
This paper presents the modeling procedure of a butt-welded joint using SolidWorks Simulation software and its behavior under loading. The software allows for the simulation of welded joints using 3D solid or shell models. The choice of model type depends on the complexity of the structure. To avoid convergence issues, the use of shell models is recommended for more complex structures [8].
For the purpose of the simulation, the tensile strength of a butt-welded joint made from aluminum plates (Al 99.5) was previously determined from experimental testing. Tensile test specimens were prepared, and since fracture occurred in the base material, the simulation used material data from the SolidWorks Simulation material database for the base material. The research results and corresponding conclusions, obtained through experimental analysis and computer simulation, can be used as recommendations regarding the reliability of the SolidWorks Simulation software for the analysis of welded joints.

MATERIAL AND METHODS

Experimental testing

For the purpose of the simulation, the tensile strength of a butt-welded joint was previously determined using aluminum (Al 99.5) specimens welded by the MIG welding process. Tensile test specimens were prepared from the welded plate in accordance with the relevant

standard [2]. The prepared specimens are shown in Figure 1, and in Figure 2, the fractured specimen after tensile testing in the testing machine.

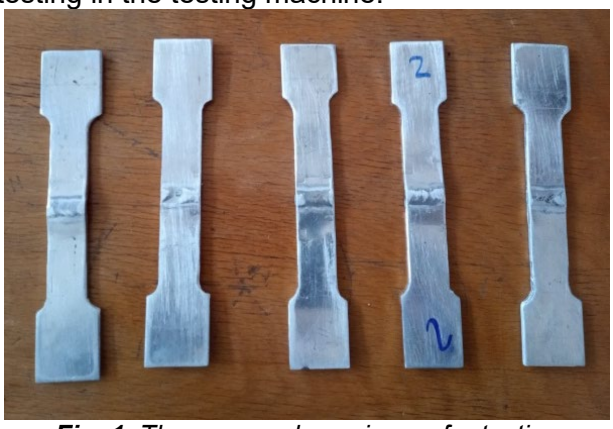


Fig. 1. *The prepared specimens for testing*



Fig. 2. *The fractured specimen after tensile testing*

The tensile strength obtained from the experiment is R_{mN} = 81,165 N/mm², and since the fracture occurred in the base material, the simulation used material data from the SolidWorks Simulation software database for the base material. The data provided by the manufacturer includes a full range of values for tensile strength and yield strength for Al 99.5, depending on the treatment condition, and one of them is shown in Table 1, [10].

Table 1. *Values for tensile strength and yield strength for one case of treatment condition*

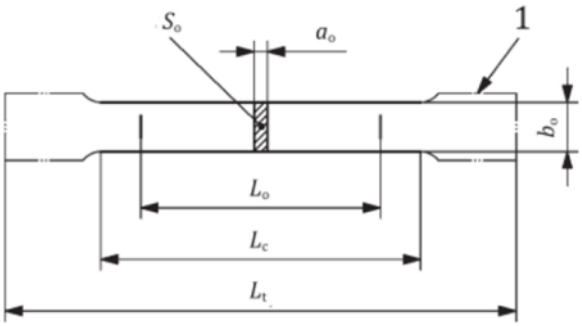
Designation	**Standard**	**Treatment condition**	**Tensile strength R_m (N/mm²)**	**Yield strength $R_{p0.2}$ (N/mm²)**
EN AW-1050A (Al 99.5)	EN 485	O/H111	65 – 95	20

The experimentally obtained R_m value fits within the specified interval.

Numerical simulation of statically loaded welded specimens.

The SolidWorks Simulation module was used to assess the strength of welded joints. The geometry of the tested specimens was modeled using 3D solid and shell models. Since sheet metal components were considered, the Sheet Metal module was applied for creating sheet parts. For sheet components, the mesh is automatically generated on the mid-surface, with the shell thickness extracted from the actual sheet thickness. When creating welded joints in either 3D solid or shell models, the welded surfaces must belong to different bodies in the CAD model.

Figure 3 shows the shape and dimensions of the specimen, while Figure 4 presents the axonometric view. The specimen thickness is a_o = 3 mm, the width b_o = 20 mm, and the total length L_t = 300 mm. The butt-welded V-joint has a weld thickness equal to the sheet thickness s = a_o = 3 mm. The loading was performed for several values of the axial tensile force F = 3.750 [N], 4.000 [N], 4.250 [N], 4.445 [N], 4.750 [N], 4.870 [N], 5.285 [N].



Width b_o	Original gauge lenght L_o	Minimum parallel lenght L_c	Approximately total lenght L_t
40 ± 0,7	200	220	450
25 ± 0,7	200	212,5	450
20 ± 0,5	80	90	300

Fig. 3. *Technical drawing of the specimen with parameter values*

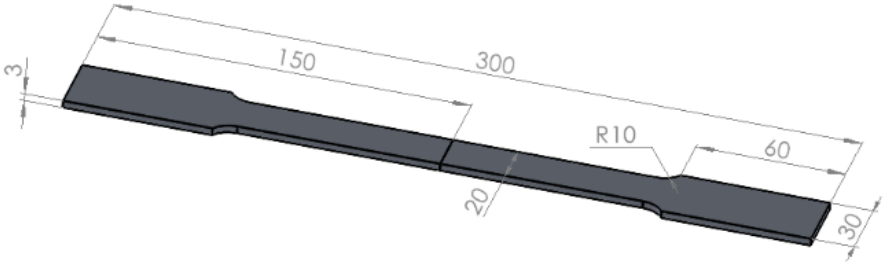


Fig. 4. *Axonometric view of the specimen with the specified dimensions*

For the purpose of the case study, a 3D model was created in the Assembly mode of SolidWorks 2023. In the SolidWorks Simulation module, supports (i.e., fixed surfaces) and external loads, namely the tensile force F, were defined (Figure 5).

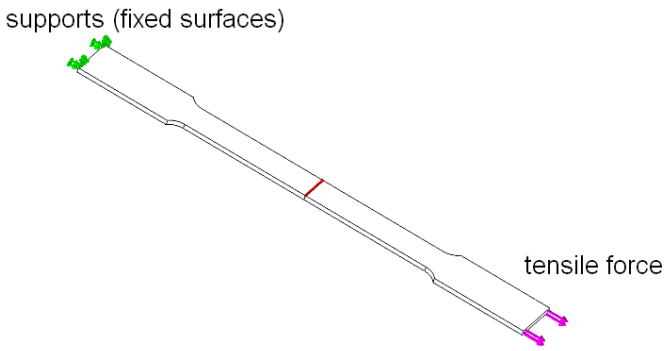


Fig. 5. *3D model of the specimen created in Assembly mode, showing the supports and the direction of the applied tensile force F*

For the specimen material, a material was selected from the software's material database, namely: Aluminium Alloys 1060-H16, with tensile strength R_{mN} = 110 N/mm^2, and yield stress R_{eN} = 105 N/mm^2. The electrode material is welding wire AlMg5, with tensile strength R_{mN} = 250 N/mm^2, and yield stress R_{eN} = 120 N/mm^2.
For the purpose of the numerical simulation, among several possible methods for static analysis of a welded joint using the finite element method, the Edge Weld Connector tool was selected, which is specifically designed for the calculation of welded joints in SolidWorks Simulation.
By applying this tool, the software automatically analyzes stresses (Von Mises stress), strains (Strain), displacements (Displacement), safety factors (Factor of Safety, FOS), as well as the required weld size (Weld Check Plot), based on the characteristics of the base material, electrode, and other relevant parameters.
The selection of the electrode is performed in the Edge Weld Connector dialog box with different electrode material definitions:
(a) European standard – electrode material equal to the weaker material of the welded joint,
(b) European standard – user-defined electrode material, and
(c) American standard – electrode material defined from the software material database.
In addition, the option for a single-sided butt V-groove weld was selected. The contact surfaces and weld edges were defined, as well as the default values for the correlation factor β_ω = 1 and the partial safety factor 1.25. The designed weld width is s = 3 mm.
Figure 6 shows a section of the generated finite element shell mesh with predefined element dimensions and density, see Table 2.

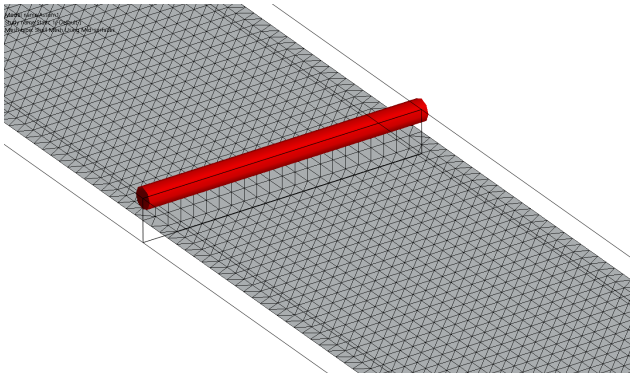


Fig. 6. *Shell mesh generated on the mid-surface of the specimen*

Table 2. *Mesh characteristics*

Mesh type	Shell mesh on the mid-surface
Mesh used	Standard mesh
Jacobian points for High quality mesh	4 points
Element size	3,647 mm
Tolerance	0,182 mm
Mesh quality	High
Number of nodes	35.631
Number of elements	17.446

After completing the finite element mesh generation process, the analysis was performed according to the specified parameters and loads, and the results of the static analysis of the welded joint were obtained. The results for numerical simulation no. 4 are presented in Figures 7–10.

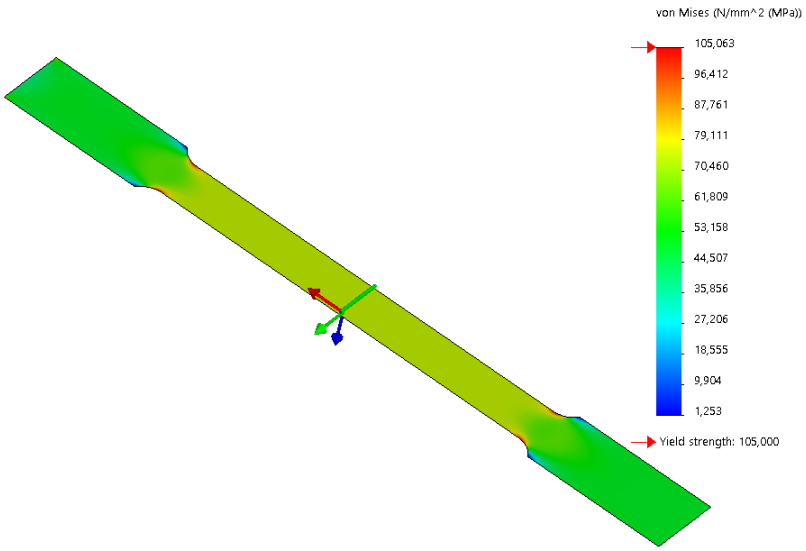


Fig. 7. *Von Mises stress distribution for the numerical simulation no. 4 (F = 4.445 N)*

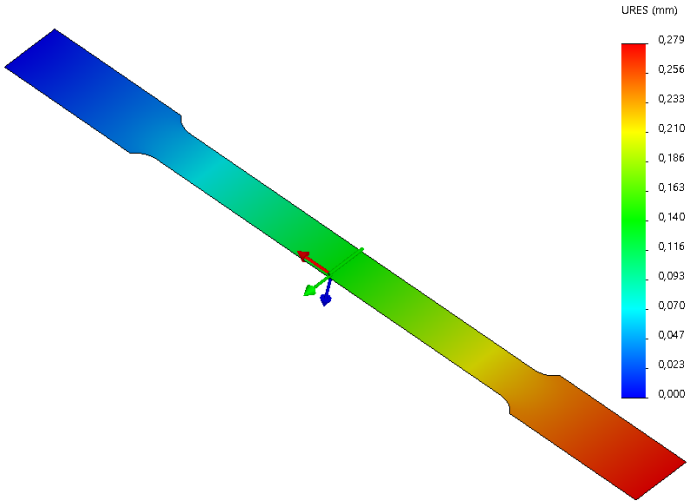


Fig. 8. *Displacement distribution for the numerical simulation no. 4 (F = 4.445 N)*

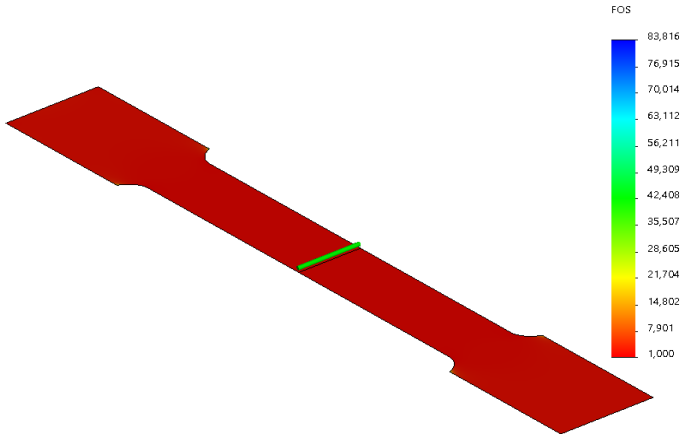


Fig. 9. *Factor of Safety for the numerical simulation no. 4 (F = 4.445 N)*

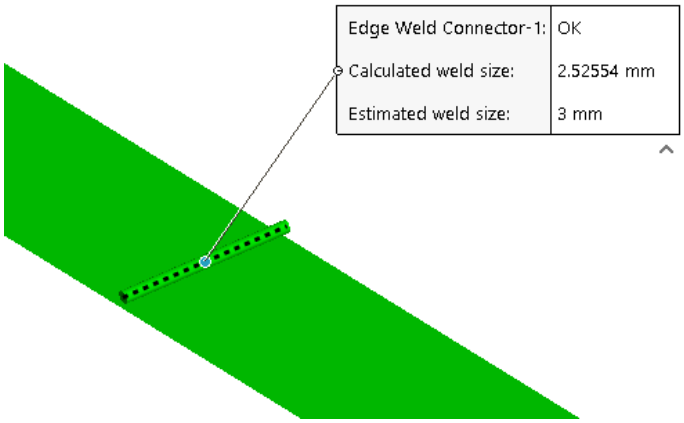


Fig. 10. *Weld size verification for the numerical simulation no. 4 (F = 4.445 N)*

RESULTS AND DISCUSSION

Based on numerical simulations with seven different values of the tensile force F = 3.750 [N], 4.000 [N], 4.250 [N], 4.445 [N], 4.750 [N] 4.870 [N], 5.285 [N] the results were obtained and are presented in Table 2.
The results of the numerical simulation indicate that the maximum allowable force is F = 4.445 N, with a safety factor of 1. The tensile stress at that point is 105,063 N/mm², and the displacement (i.e., elongation) is 0,279 mm. The weld size check (2,525 mm < 3 mm) indicates that failure would occur in the base material. A comparison of the results obtained from the experiment and the numerical simulation is presented in Table 3.

Table 3. *Presentation of results obtained from numerical simulations with different values of the axial tensile force F*

Simulation no.	**F** [N]	**Von Mises Stress** [MPa]	**Displacement** [mm]	**Factor of Safety, FOS**	**Weld Check Plot** [mm]
1	3.750	88,636	0,236	1,185	2,130 < 3
2	4.000	94,545	0,251	1,111	2,272 < 3
3	4.250	100,454	0,267	1,045	2,414 < 3
4	4.445	105,063	0,279	1	2,525 < 3
5	4.750	112,272	0,299	0,935	2,698 < 3
6	4.870	115,108	0,306	0,912	2,767 < 3
7	5.285	124,917	0,332	0,841	3,002 > 3

By observing the results in Table 3, it can be seen that failure occurs in the base material during the 5th simulation, at a tensile force of 4.750 N, which is very likely realistic, as fracture occurred experimentally at 4.869,9 N (factor of safety is 0,935). It can also be concluded that if the base material had not failed in simulations 5 or 6, failure would have occurred in the weld metal during the 7th simulation, at a force of 5.285 N (weld check plot is 3,002 > 3).

Table 4. *Comparison of results obtained from experiment and numerical simulation*

Parameters	**Values**
Tensile force F obtained from the experiment [N]	4.869,9
Tensile force F obtained from the numerical simulation [N]	4.445
Tensile strength R_m obtained from the experiment [N/mm^2]	81,165
Von Mises stress obtained from the numerical simulation [N/mm^2]	105,063

By analyzing the regions where the maximum Von Mises stress values obtained from the simulation occur, it can be observed that these are the areas of the specimen with a radius

R=10 mm. However, the fracture region of the specimen in the performed experiment is located in the central part of the specimen next to the welded joint. For this reason, an analysis was carried out using the Probe tool, which allows reading values for different regions of the specimen.
Figure 11 shows the Von Mises stress value obtained from an analysis using the Probe tool. In this case, the numerical simulation was performed with a tensile force of F = 4.869.9 N, which is precisely the force at which the specimen fractured in the experiment. The Von Mises stress value of 81,165 N/mm² obtained experimentally corresponds to the average stress value in the fracture region of the specimen obtained from this numerical simulation.

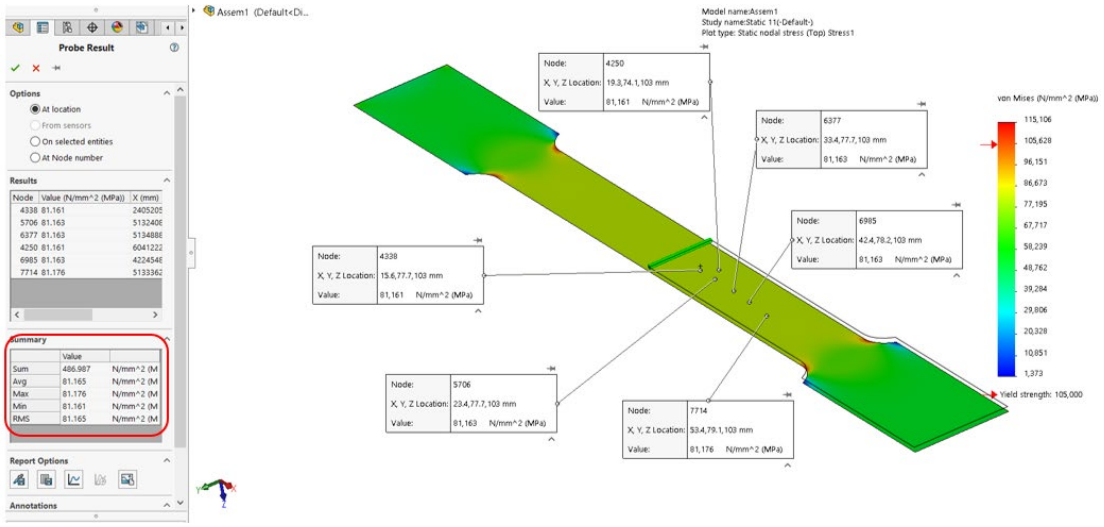


Fig. 11. *Results obtained from an analysis using the Probe tool (F = 4.869,9 N, Von Mises stress value = 81,165 N/mm²)*

The comparison between the experimental results and the average Von Mises stress values obtained using the Probe tool in the numerical simulation was carried out (Table 5).

Table 5. *Comparison of Experimental Results and Average Von Mises Stress (Probe Tool)*

Parameters	**Values**
Tensile force F obtained from the experiment [N]	4.869,9
Tensile strength R_m obtained from the experiment [N/mm^2]	81,165
Average Von Mises stress value obtained from the numerical simulation [N/mm^2]	81,165

CONCLUSION

The SolidWorks Simulation software has proven to be an efficient tool for the analysis of welded joints. Three different methods for analyzing welded joints in SolidWorks Simulation can be distinguished:

- All components can be modeled as solid bodies (Solid Mesh),
- The weld can be treated as a beam (Beam Mesh) while the other components remain solid bodies, and
- Instead of solid bodies, shell meshes (Shell Mesh) can be used along with the Edge Weld Connector tool.

The Weld Check Plot tool has proven to be effective in verifying the parameter values of the welded joint.
The results obtained through computer simulation differ to some extent from those obtained experimentally. This may be due to the different mechanical properties of the tested material compared to the values defined in the software, as it has been shown that the tensile strength of this material falls within a range of possible values.

Furthermore, the results indicate the need for continued research to assess the reliability of the SolidWorks Simulation software in the analysis of various welded joints, including both butt and fillet welds.

REFERENCES

[1] Lindgren, L.E., Numerical modelling of welding, Comput. Methods Appl. Mech. Engrg., 2006, (195), p 6710–6736.
[2] EN ISO 4136:2013: Ispitivanje sa razaranjem zavarenih spojeva metalnih materijala - Poprečno ispitivanje zatezanjem, 2013.
[3] Majstorović, A., Đukić, V., Ispitivanje mašinskih materijala - uputstvo, Naučna knjiga, Beograd 1989.
[4] Seferijan, D., Metalurgija zavarivanja, Građevinska knjiga, Beograd, 1969.
[5] Miltenović, V., Mašinski elementi, Mašinski fakultet u Nišu, Niš 2009.
[6] Al-Samhan, A., Darwish, S.M.H., Finite element modeling of weld-bonded joints, Journal of Materials Processing Technology, 2003, (142), p 587.598.
[7] Griškevičius, P., Urbas, M. Capas, V. Kozlovas, A., Modeling of Welded Connections in SolidWorks Simulation, Mechanika 2011: Proceedings of the 16th International Conference, 2011., p 104-108.
[8] Zdraveski, F., Bogatinoski, Z., Trajanoska, B., Modeliranje single-fillet preklopnog spoja u Solidworks simulaciji, Journal of Applied Engineering Science. 2016;14(1):21-7. doi: 10.5937/jaes14-8900
[9] Mohammadi S., Extended finite element method for fracture analysis of structure, Blackwell Publishing Ltd., Oxford, UK, 2008.
[10] https://www.thyssenkrupp-materials-processing-europe.com/en/aluminum/alloy-group-1000-or-en-aw-1050-a-or-en-aw-1200a/en-aw-1050a

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ANALYSIS OF CO_2 EMISSIONS IN SLOT MILLING OF C45E STEEL

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Abstract: This study focuses on analysing CO_2 emissions per volume of material removed in slot milling of unalloyed medium carbon steel C45E using solid carbide slot milling cutter. A full factorial design was employed to arrange the main cutting parameters, i.e., depth of cut, feed per tooth and cutting speed, at three levels. CO_2 emissions data for the various cutting parameter combinations were obtained using the tool and cutting data recommendation system of the cutting tool manufacturer (Walter GPS). The analysis included evaluation of main, interaction, and quadratic effects, leading to the development of a predictive model for estimating CO_2 emissions per volume of material removed. In addition, the optimal combination of cutting parameter values for minimization of CO_2 emissions was determined.
Key words: milling, CO_2 emissions, full factorial design, C45E steel, prediction

INTRODUCTION

Until recently the manufacturing companies focused on productivity, cost and profit rate. However, due to the gradually increasing energy prices and rising green awareness, sustainable and environmentally friendly manufacturing has become the goal of a growing number of companies. Actually, it has been a major role player in the Industry 4.0 transformation [1]. The scientific society and manufacturing practice are constantly investigating the possibilities of incorporating circular economy models, improving energy efficiency and minimizing/eliminating any kind of waste to create a more environmentally friendly manufacturing industry [2]. To this end, recent investigations and applications of machining technologies have expanded beyond analysing key technological and economic performance indicators to also include considerations of sustainability, green practices, and environmental impact. Related to milling technology, several previous research studies have addressed these important aspects.
Sivalingam et al. [3] evaluated sustainability indicators, including energy consumption and carbon emissions, in milling of aluminium hybrid composite material under different ecofriendly cooling strategies, such as dry, minimum quantity lubrication (MQL), LCO_2, MQL + LCO_2. The authors introduced overall equipment effectiveness (OEE) as the key factor indicating the effectiveness of any production equipment performance and found that hybrid cooling (CO_2 + MQL) resulted the highest OEE of 95.63% and very low carbon emission of 0.6 kgCO_2. Mishra et al. [4] analysed the impact of the cutting parameters on the carbon emissions in milling of S50C carbon steel. Carbon emissions data was predicted using various machine learning methods. XGBoost showed the best accuracy. Spindle speed was identified as the most influencing factor affecting the carbon emissions. Xie et al. [5] studied optimization of cutting parameters in multi-pass rough and fine milling, aiming at energy efficiency (energy-saving), carbon emissions efficiency (low-carbon) and cost efficiency (low-cost). The authors focused on the dynamic characteristics of energy consumption and carbon emissions. Kanan et al. [6] analysed the impact of three cutting environments (dry cutting and two MQL techniques), cutting speed, and feed rate on carbon emissions, surface quality, and microhardness in milling of AZ31 magnesium alloy. The cutting environment MQL + bio-oils + kaolinite generated the lowest carbon emissions and surface roughness value. Ozturk and Kara [7] investigated the machinability of 6061 aluminium alloy. The goal of the authors was to optimize the cutting parameters (cutting speed, depth of cut, feed rate, and cooling method) to yield minimum surface roughness with minimum energy consumption in slot milling operation. The energy consumption values of both the spindle and X-axis servo motors during chip removal were examined. Pereira et al. [8] proposed cryogenic cooling with external MQL lubrication (CryoMQL) working along with CO_2 as internal coolant for milling of Inconel 718. This cooling

technique proved to be ecofriendly alternative to substitute oil emulsions in industrial environments at medium-term. Khanna et al. [9] compared two sustainable cutting fluid approaches, dry and LCO_2, based on machining performance indicators, like temperature, modulus of cutting force, tool wear, surface roughness, power consumption, and life cycle assessment (LCA) analysis for end milling of glass fiber reinforced polymer. The cutting condition of LCO_2 has been found to be superior in terms of machining performance. Tlhabadira et al. [10] developed a model for the optimization of the energy consumption during the milling operation of titanium alloy (Ti6Al4V) without cooling and with air cooling, using the response surface methodology (RSM). The energy consumption was observed to increase with a decrease in the feed rate and an increase in the cutting speed and the axial depth of cut, and when the machining process was not subjected to cooling. Nguyen et al. [11] considered multi-objective optimization of cutting parameters in dry milling of stainless steel 304, aiming to simultaneously maximize power factor and minimize the energy consumption and surface roughness. The results showed that the responses were primarily influenced by the feed rate and cutting speed. Daniyan et al. [12] carried out the LCA of the milling operation of titanium alloy (Ti6Al4V) under the cooling and non-cooling conditions. Deng et al. [13] presented the carbon utilisation efficiency, defined as the ratio of the carbon emission of material removal to the whole carbon emission in manufacturing process, as the comprehensive evaluation index in low carbon manufacturing. Carbon utilisation efficiency model was established for milling process. Duc et al. [14] suggested using Al_2O_3 soybean oil-based nanofluid rather than oil-in-water emulsion for MQL system, since it not only meets the technical requirements but also is suitable to the green and environmentally friendly machining. Markopoulos et al. [15] investigated the effect of feed peer tooth, cutting speed, and depth of cut on surface roughness, cutting force, cutting power, machining cost, and carbon dioxide emission for slot milling of AISI O1 hardened steel. The authors determined cutting parameter values for eco-benign machining. Jamil et al. [16] evaluated the performance of MQL, LN_2, and CO_2-snow approaches in milling of Ti-6Al-4V titanium alloy and compared it to dry conditions at varying cutting conditions. Through a comprehensive set of experiments the authors evaluated sustainability measures (processing time, specific cutting energy, energy efficiency, carbon emissions) and machining characteristic (tool wear, surface roughness, and cutting temperature).

As could be observed from literature review, there is a greater number of empirical modelling and optimization studies related to LCA, carbon emissions, energy consumption, energy efficiency, power consumption, and use of sustainable cutting fluids in milling. With this in mind, the present study focuses on the analysis of CO_2 emissions per volume of material removed in slot milling of unalloyed medium carbon steel C45E. Analysis of results involved determination of statistically significant effects, analysis of parameter effects, development of non-linear prediction model and identification of stationary point which yields minimal CO_2 emissions per volume of material removed.

MATERIAL AND METHODS

Single-pass slot milling was applied for machining straight slot with two open ends. Slot width was 16 mm, while slot length was 100 mm. The workpiece material was unalloyed medium carbon steel C45E (Ck45 DIN 17200, hardness 207 HB). The machine tool was the machining center with the maximum spindle speed of n_{max} = 20000 rpm, maximum cutting power of P_{cmax} = 30 kW, and the maximum cutting torque of M_{cmax} = 120 Nm.

Walter was selected as cutting tool manufacturer. The cutting tool was MC326 Supreme solid carbide shoulder/slot milling cutter for roughing and finishing Walter MC326-16.0A4BCJ-WK40TF (cutting diameter of D_c = 16 mm, cutting edge length of L_c = 16 mm, number of teeth z = 4, helix angle of λ = 50°, (axial) depth of cut for slot milling $a_p \leq 0.9 \times D_c$ ($a_p \leq 14.4$ mm), grade of WK40TF (coated carbide)). Cutting parameter ranges and levels were selected considering availability and capabilities of the tool and cutting data recommendation system of the cutting tool manufacturer (Walter GPS) and recommended cutting conditions for the milling cutter.

The virtual experiment was conducted in accordance with the full factorial design while varying three main cutting parameters, i.e., depth of cut, feed per tooth and cutting speed (Table 1).

Table 1. *Cutting parameter levels used in the experiment*

Parameter	Level 1	Level 2	Level 3
Depth of cut a_p [mm]	4	8	12
Feed per tooth f_z [mm/tooth]	0.04	0.09	0.14
Cutting speed v [m/min]	164	206	248

For all combinations of cutting parameter levels CO_2 emissions per component (gCO_2) produced by machining operation and idle machine run were obtained using the tool and cutting data recommendation system of the cutting tool manufacturer (Walter GPS). Afterwards, CO_2 emissions per volume of material removed (gCO_2/cm^3) was calculated by dividing total CO_2 emissions per component with the volume of material removed.

RESULTS AND DISCUSSION

Using the standard RSM procedure main, interaction and quadratic effects were estimated (Table 2).

Table 2. *Summary of estimated main, interaction and quadratic effects*

Term	Coefficient	T	p
Constant	0.35201	7.637	0.000
a_p	-0.34097	-15.980	0.000
f_z	-0.38757	-18.164	0.000
v	-0.13002	-6.094	0.000
$a_p \times a_p$	0.17048	4.613	0.000
$f_z \times f_z$	0.21545	5.830	0.000
$v \times v$	0.02817	0.762	0.456
$a_p \times f_z$	0.21120	8.082	0.000
$a_p \times v$	0.07092	2.714	0.015
$f_z \times v$	0.08116	3.106	0.006
$S = 0.0905$ $R^2 = 0.978, R^2_{adj} = 0.966, R^2_{pred} = 0.937$			

The analysis of results indicates that all linear effects of cutting parameters are significant. In addition, small p-values of interaction and quadratic effects suggest the presence of curvature in the response surface. Among these, however, quadratic effect of the cutting speed was not statistically significant. Coefficient of determination (R^2) shows that 97.8% of total variability of CO_2 emissions per volume of material removed is explained by all terms. Based on predicted coefficient of determination (R^2_{pred}), the model is expected to explain 93.7% of the variability in response for arbitrarily chosen values of depth of cut, feed per tooth and cutting speed.
To validate the appropriateness and predictive capability of the quadratic model, ANOVA was conducted, as shown in Table 3. The ANOVA results indicate that all model terms (linear, interaction and quadratic) are significant as evidenced by the Fischer's F-test and p-values of 0.000.

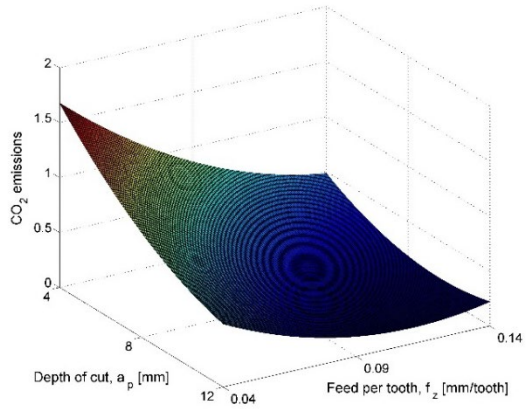
Table 3. *ANOVA results of the prediction model*

Source of variation	Sum of squares	Degree of freedom	Mean square	F	p
Second order model	6.23311	9	0.69257	84.51	0.000
Linear	5.10079	3	1.70026	207.48	0.000
Interaction	0.67467	3	0.22489	27.44	0.000
Quadratic	0.45766	3	0.15255	18.62	0.000
Residual error	0.13931	17	0.00819		
Total	6.37242	26			

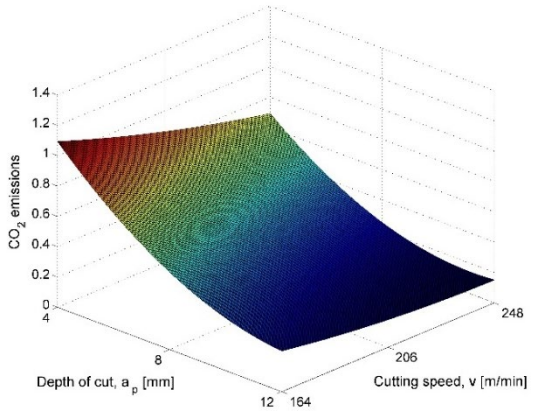
Based on prior analyses, CO_2 emissions per volume of material removed, was modelled using a full quadratic model to capture the main, interaction, and quadratic effects of depth of cut, feed per tooth, and cutting speed. The coded form of the prediction model is as follows:

$$CO_2\ emission = 0.35201 - 0.340975x_1 - 0.38757x_2 - 0.13002x_3 + 0.17048x_1^2 + 0.21545x_2^2 + 0.02817x_3^2 + 0.2112x_1x_1 + 0.07092x_1x_3 + 0.08116x_2x_3 \quad (1)$$

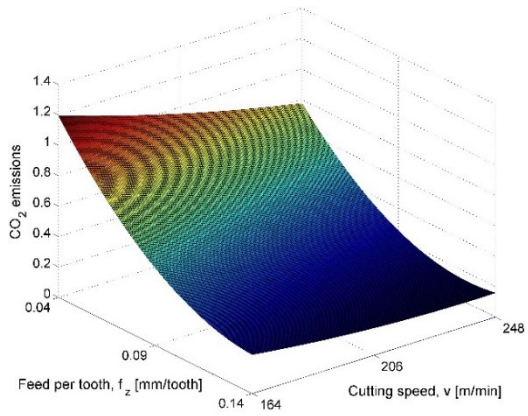
where the coded variables x_1, x_2 and x_3 represent depth of cut (a_p), feed per tooth (f_z) and cutting speed (v), respectively.
The derived RSM model was further visualized by developing surface plots (Fig. 1 a), b), c)), allowing the detailed analysis of the main and two-way interaction effects of cutting parameters on the CO_2 emissions per volume of material removed.



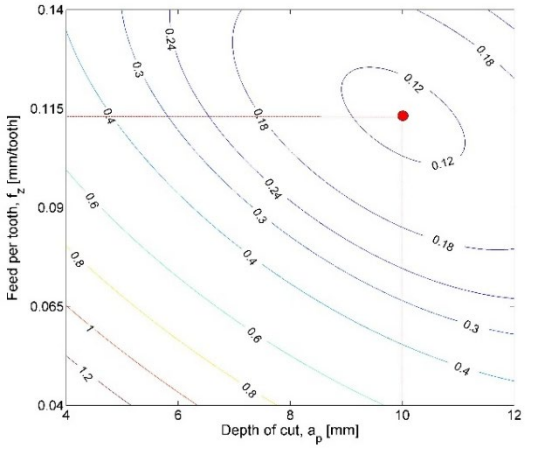
a) v = 206 m/min



b) f_z = 0.09 mm/tooth



c) a_p = 8 mm



d) Contour plot with identified optimum

Fig. 1. 3D surface plots of the developed prediction model (a), b) and c)) and contour plot showing stationary point (d))

As could be observed from Fig. 1, increasing the value of any cutting parameter leads to a decrease in CO_2 emissions per volume of material removed. However, the feed per tooth has the most significant effect followed by the depth of cut and the cutting speed. The clearly visible patterns of developed surface plots suggest nonlinear nature of the effects of the depth of cut and feed per tooth, which is in accordance with previously performed analysis that showed statistically significant quadratic effects of the depth of cut and feed per tooth.
The existence of interaction effects and qualitative change in the parameter effects can be observed in Fig. 1 a). Namely, for small depths of cuts an increase in feed per tooth non-linearly significantly decreases CO_2 emissions per volume of material removed. For intermediate and high values of the depth of cut, an increase in feed per tooth also decreases CO_2 emissions per volume of material removed, wherein that decrease is much smaller in quantitative sense, and it is realized according to a pattern with less curvature. Moreover, there is a qualitative change in the effect of the feed per tooth at the highest depth of cut. As could be observed, for highest depth of cut, an increase in feed per tooth up to 0.11 mm/tooth decreases CO_2 emissions per volume of material removed. However, further increase in feed per tooth values results in a slight increase in CO_2 emissions per volume of material removed. Since response of interest was accurately modelled by the second-order model, it is necessary to determine the optimum settings, i.e., optimal combination of cutting parameter values, since this is a necessary step to improve machining efficiency and quality [17]. To this aim an attempt has been made to identify a stationary point and the most straightforward way to determine the nature of the stationary point is construction of contour plots, or more formal analysis, i.e., canonical analysis [18].
The stationary point in terms of the natural values of cutting parameters was obtained as: depth of cut a_p = 10 mm, feed per tooth f_z = 0.11 mm/tooth, and cutting speed v = 248 m/min. Based on these values, and using variable transformations one can estimate minimum response, i.e., CO_2 emission per volume of material removed at the stationary point with the value of 0.11 gCO_2/cm^3. The nature of the response surface can be verified from Fig. 1 d).

CONCLUSION

The present study dealt with analysis of the effects of depth of cut, feed per tooth and cutting speed on CO_2 emissions per volume of material removed in single-pass slot milling of unalloyed medium carbon steel C45E. The following conclusions can be derived from the analyses and results obtained:

- CO_2 emissions per volume of material removed is mostly affected by the feed per tooth, followed by depth of cut and cutting speed.
- All main effects of the depth of cut, feed per tooth and cutting speed were found to be statistically significant, along with all interaction effects, as well as quadratic effects of the depth of cut and feed per tooth.
- Generally, an inverse relationship exists between CO_2 emissions per volume of material removed and cutting parameters. Increasing depth of cut, feed per tooth, or cutting speed typically leads to a decrease in CO_2 emissions per unit volume, as higher machining efficiency reduces the environmental impact relative to the amount of material removed.
- It may be argued that for a given cutting speed there exists a particular combination of depth of cut and feed per tooth that yields minimal CO_2 emissions per volume of material removed.

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REFERENCES

[1] Gupta, K.: A Review On Green Machining Techniques, Procedia Manufacturing, Vol. 51, pp. 1730-1736, 2020.
[2] Barać, M., Vitković, N., Stanković, Z., Rajić, M., Turudija, R.: Description and Utilization of an Educational Platform for Clean Production in Mechanical Engineering, Spectrum of Mechanical Engineering and Operational Research, Vol. 1, pp. 145-158 (2024).
[3] Sivalingam, V., Zhou, Q., Selvam, B., Sun, J., Pandiyan, K., Gupta, M.K., Korkmaz, M.E.: A mathematical approach of evaluating sustainability indicators in milling of aluminium hybrid composite by different eco-friendly cooling strategies, Sustainable Materials and Technologies, Vol. 36, Article ID: e00605, 14 pages, 2023.
[4] Mishra, A., Yau, H.T., Kuo, P.H., Wang, C.C.: Achieving sustainability by identifying the influences of cutting parameters on the carbon emissions of a milling process, The International Journal of Advanced Manufacturing Technology, Vol. 135, pp. 5409-5427, 2024.
[5] Xie, Y., Dai, Y., Zhou, H., Liu, J., Zhang, C.: An optimization method of processing parameters of multi-pass CNC milling towards energy and carbon emission efficiency, The International Journal of Advanced Manufacturing Technology, Vol. 128, pp. 4749-4761, 2023.
[6] Kanan, M., Zahoor, S., Habib, M.S., Ehsan, S., Rehman, M., Shahzaib, M., Khan, S.A., Ali, H., Abusaq, Z., Hamdan, A.: Analysis of Carbon Footprints and Surface Quality in Green Cutting Environments for the Milling of AZ31 Magnesium Alloy, Sustainability, Vol. 15, Article ID: 6301, 18 pages, 2023.
[7] Ozturk, B., Kara, F.: Calculation and Estimation of Surface Roughness and Energy Consumption in Milling of 6061 Alloy, Advances in Materials Science and Engineering, Vol. 2020, Article ID: 5687951, 12 pages, 2020.
[8] Pereira, O., Celaya, A., Urbikaín, G., Rodríguez, A., Fernández-Valdivielso, A., López de Lacalle, L.N.: CO_2 cryogenic milling of Inconel 718: cutting forces and tool wear, Journal of Materials Research and Technology, Vol. 9, pp. 8459-8468, 2020.
[9] Khanna, N., Rodríguez, A., Shah, P., Pereira, O., Rubio-Mateos, A., López de Lacalle, L.N., Ostra, T.: Comparison of dry and liquid carbon dioxide cutting conditions based on machining performance and life cycle assessment for end milling GFRP, The International Journal of Advanced Manufacturing Technology, Vol. 122, pp. 821-833, 2022.
[10] Tlhabadira, I., Daniyan, I.A., Masu, L., Mpofu, K.: Development of a model for the optimization of energy consumption during the milling operation of titanium alloy (Ti6Al4V), Materials Today: Proceedings, Vol. 38, pp. 614-620, 2021.
[11] Nguyen, T.T., Mia, M., Dang, X.P., Le, C.H., Packianather, M.S.: Green machining for the dry milling process of stainless steel 304, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Vol. 234, pp. 881-899, 2019.
[12] Daniyan, I., Mpofu, K., Bello, K., Muvunzi, R.: Life cycle assessment for the milling operation of titanium alloy (Ti6Al4V), Procedia CIRP, Vol. 105, pp. 811-816, 2022.
[13] Deng, Z., Lv, L., Huang, W., Wan, L., Li, S.: Modelling of carbon utilisation efficiency and its application in milling parameters optimisation, International Journal of Production Research, Vol. 58, pp. 2406-2420, 2020.

[14] Duc, T.M., Long, T.T., Tuan, N.M.: Performance Investigation of MQL Parameters Using Nano Cutting Fluids in Hard Milling, Fluids, Vol. 6, Article ID: 248, 15 pages, 2021.
[15] Markopoulos, A.P., Karkalos, N.E., Mia, M., Pimenov, D.Y., Gupta, M.K., Hegab, H., Khanna, N., Aizebeoje Balogun, V., Sharma, S.: Sustainability Assessment, Investigations, and Modelling of Slot Milling Characteristics in Eco-Benign Machining of Hardened Steel, Metals, Vol. 10, Article ID: 1650, 17 pages, 2020.
[16] Jamil, M., Zhao, W., He, N., Gupta, M.K., Sarikaya, M., Khan, A.M., R, S.M., Siengchin, S., Pimenov, D.Y.: Sustainable milling of Ti-6Al-4V: A trade-off between energy efficiency, carbon emissions and machining characteristics under MQL and cryogenic environment, Journal of Cleaner Production, Vol. 281, Article ID: 125374, 14 pages, 2021.
[17] Kawecka, E., Perec, A., Radomska-Zalas, A.: Use of the Simple Multicriteria Decision-Making (MCDM) Method for Optimization of the High-Alloy Steel Cutting Process by the Abrasive Water Jet, Spectrum of Mechanical Engineering and Operational Research, Vol. 1, pp. 111-120, 2024.
[18] Montgomery, D.C.: Design and Analysis of Experiments, 9th Edition, John Wiley & Sons, Hoboken, NJ, 2017.

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ENHANCING EDUCATIONAL QUALITY THROUGH VIRTUAL REALTY

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Abstract: Technology development today have great impact on education. Usage of modern tools became imperative for increasing the comprehension of learning materials. In area of product development, CAD/CAM/CAE software have big role in achieving the learning outcomes. The next step represents the software combination with Virtual Reality (VR). In such environment students can achieve better understanding of product design elements. This paper provides the insight of the role of Virtual Reality in education in area of Industrial design.
Key words: virtual reality, education, product development, virtual prototype.

INTRODUCTION

Technology development today has a strong impact on education, and the use of modern digital tools has become imperative for improving the comprehension of learning materials. In the area of product development education, understanding complex product structures, assemblies, and functions represents a significant challenge when only traditional teaching methods are applied. Conventional approaches based on lectures, technical drawings, and screen-based CAD models often limit students' ability to fully visualize and interpret product design elements.

CAD/CAM/CAE software plays an important role in supporting learning outcomes by enabling students to create, analyze, and modify digital product models. Through these tools, students gain knowledge about geometry, materials, manufacturing processes, and performance analysis. However, interaction with these models is still mostly limited to two-dimensional displays, which can reduce spatial understanding and make it difficult to interpret complex assemblies and internal components.

The next step in the development of educational tools for product development is the integration of CAD/CAM/CAE software with Virtual Reality (VR). In a VR-based learning environment, virtual prototypes can be experienced in an immersive and interactive manner [1,2]. Students are able to observe products at real scale, explore assemblies from different perspectives, and inspect internal structures that are not easily accessible in physical or screen-based models. This immersive visualization significantly improves the understanding of product design elements and their relationships within the overall system.

Virtual Reality also supports better understanding of virtual prototypes and assembly by allowing students to interact with them dynamically. Components can be assembled and disassembled, mechanisms can be observed in motion, and functional behavior can be analyzed in a realistic environment. Such interaction helps students identify design issues at early stages, such as poor accessibility, interference between parts, or ergonomic limitations. As a result, students develop a more comprehensive understanding of the product development process and the importance of design validation before physical prototyping. On Fig. 1 the different applications of Virtual Assembly prototyping is shown [3]



Fig.1. *Different applications for virtual assembly simulation in prototyping [3]*

Furthermore, the use of VR in education provides active and experiential learning [4]. Instead of passively observing models, students actively explore and evaluate virtual prototypes, which demandes engagement and knowledge retention. This approach also reflects modern industrial practice, where virtual prototyping and digital validation play a key role in reducing development time and costs. [5]

MATERIAL AND METHODS

Example of VR implementation for education

Technology development today has enabled the application of Virtual Reality (VR) as an effective tool in education, particularly in the area of product development and virtual prototyping. In order to achieve a realistic presentation and detailed analysis of a developed 3D model, the insertion and visualization of the model were performed using the eDrawings software environment combined with VR equipment (Fig. 2). This process was carried out in the laboratory of the Higher Technical College of Applied Sciences in Zrenjanin.



Fig. 2. *HTC Vive Cosmos virtual headset*

VR equipment used in this case study shown on Fig. 1. has the following characteristics shown in Table 1:

Table 1. *Basic specifications of the HTC Vive Cosmos VR headset*

Display (type/size)	Two LCD RGB displays, 3.4 inches per panel
Resolution	1440 × 1700 pixels per eye, total 2880 × 1700 pixels
Refresh rate	90 Hz
Field of view (FOV)	Approximately 110 degrees
Tracking	Inside-out tracking using 6 cameras; no external base station required for basic use
Recommended room scale	Minimum ~2 m × 1.5 m for room-scale mode
Supported connections/ports	DisplayPort 1.2, USB 3.0 / USB-C for data and power; proprietary port for modifications (mods)
Interpupillary distance adjustment (IPD)	Yes, IPD adjustment available
Audio	Built-in on-ear headphones, integrated microphones
Design/comfort	Flip-up front section (display can be lifted like a visor), suitable for users who wear glasses
Weight	Approximately 702 g

By loading the 3D model into the eDrawings software, it became possible to analyze the model in a virtual environment and gain a more comprehensive understanding of its structure and functionality. After opening the desired model file, the software enabled further interaction and preparation for VR visualization.

Once the virtual reality module was activated, the model of the robotic arm was displayed in its real dimensions and from multiple viewing angles (Fig. 3). This approach provides a significantly better understanding of spatial relationships within the assembly compared to classical 3D visualization on a computer screen. One of the most important functionalities within the VR environment is the Explode option, which allows the assembly to be decomposed into individual components (Fig. 4). In this way, each part of the robotic arm can be observed separately, enabling detailed inspection of shape, size, and position in relation to the overall structure.

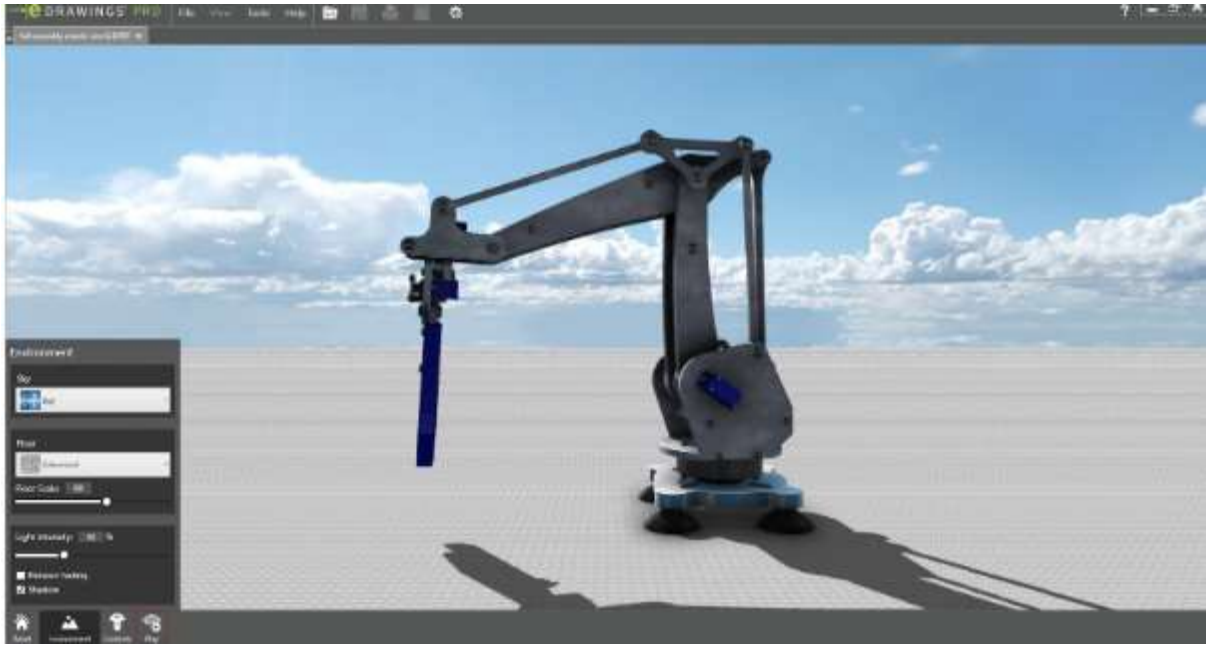


Fig. 3. *Display of robotic arm in VR environment*



Fig. 4. *Exploded view of robotic arm in VR environment*

An additional advantage of VR visualization is the possibility of interacting with individual components by virtually "grasping" them (Fig. 5), which creates a realistic perception of the product and improves comprehension of assembly logic. The software also allows annotations to be written directly on the model, enabling visual marking of critical components, adding comments, and proposing design modifications. This feature significantly improves team communication, as all observations and suggestions can be clearly shared within the same virtual environment.

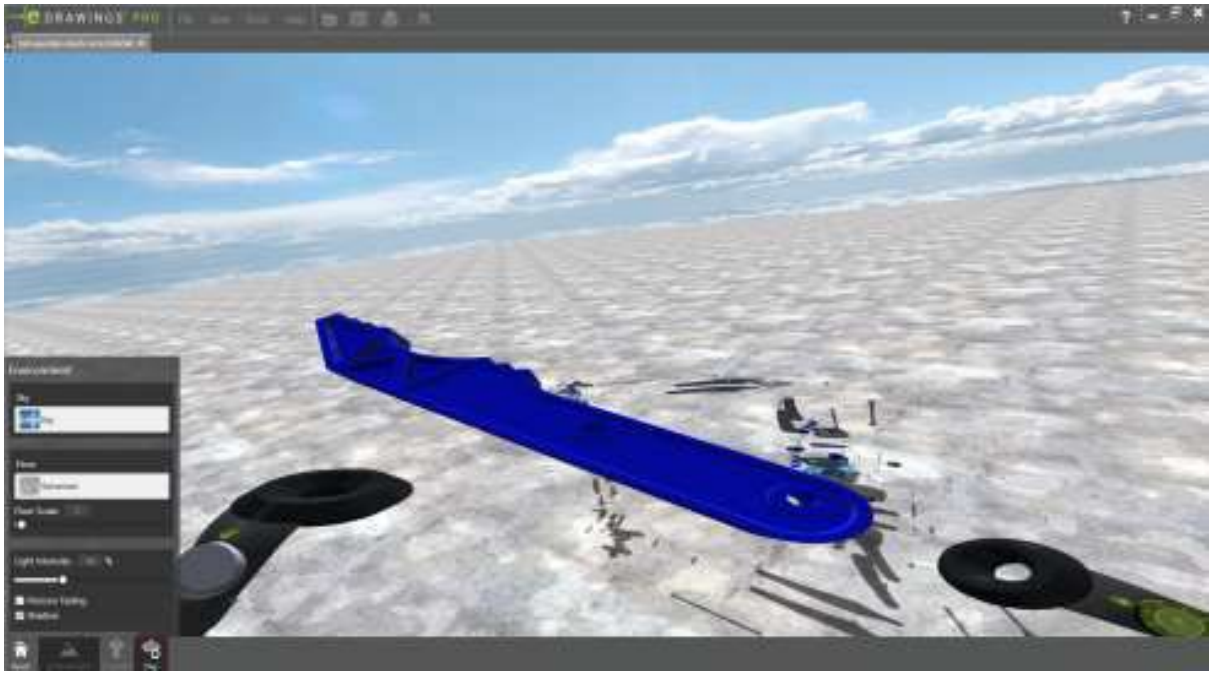


Fig. 5. *Interaction with individual parts*

Furthermore, eDrawings offers additional tools that enhance model verification and analysis, such as dimension measurement (Measure), sectional views (Section view), and various display controls (Fig. 6). These functionalities support precise evaluation of product geometry and improve both individual and collaborative work in educational and engineering practice.

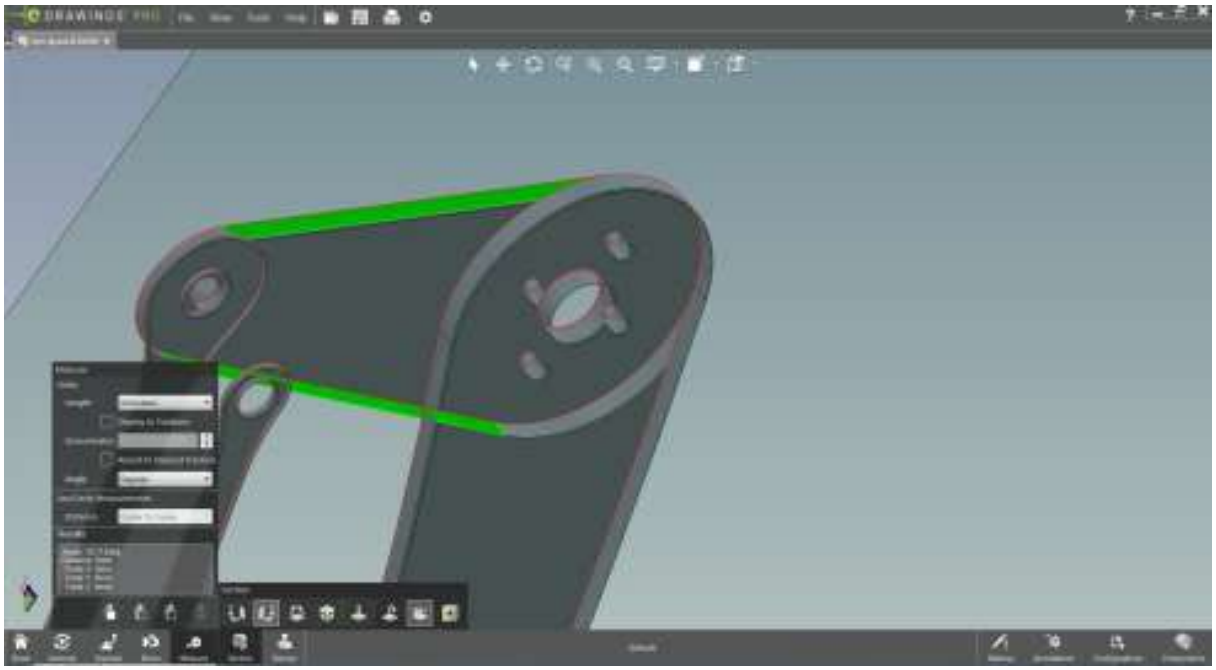


Fig. 6. *Display of additional tools in eDrawings*

RESULTS AND DISCUSSION

HTC Vive Cosmos headset provides high image resolution, a wide field of view, and inside-out tracking, which eliminates the need for external base stations and simplifies setup. Such characteristics make it suitable for educational use, 3D model inspection, virtual presentations, and assembly visualization. Although certain limitations exist, particularly in tracking precision under poor lighting conditions, the system provides sufficient performance for learning and product development analysis. Some of the advantages and disadvantages of this VR setup are:
Advantages:

- High resolution and image quality
- Simplified tracking using inside-out tracking with six cameras
- Comfort and ease of use with flip-up design
- Integrated audio system
- Flexibility and expandability through modular accessories

Disadvantages:

- Tracking issues in low-light conditions or when controllers are occluded
- Ergonomic limitations, including light leakage and maintaining optimal viewing position
- Controllers require AA batteries
- Relatively high price compared to some competitors

With the usage of eDrawings, the model was transferred directly into the virtual environment, where it could be observed from all directions and analyzed in a realistic manner. The VR module enables users to manipulate individual parts, rotate them in space, observe sectional views, and measure distances, angles, and radii. This level of interaction significantly improves understanding of the virtual prototype and allows students to better comprehend the structure, functionality, and design logic of the product.

CONCLUSION

Virtual reality have important role in improving educational processes, especially in the area of product development. Traditional teaching methods, based mainly on lectures, technical drawings, and screen-based CAD models, often limit the understanding of complex assemblies and product structures. Although CAD/CAM/CAE software significantly contributes to achieving learning outcomes, its integration with Virtual Reality represents a further step in improving the educational process.

The application of VR enables students to experience virtual prototypes in an immersive environment, where products can be observed at real scale and analyzed from multiple perspectives. As shown in this paper, the use of VR in combination with eDrawings software provides a better understanding of spatial relationships, assembly logic, and functional characteristics of product designs. Interactive features such as exploded views, manipulation of individual components, and measurement tools contribute to clearer interpretation of product design elements and early identification of potential design issues.

VR-based visualization supports active learning and increases student engagement, leading to improved comprehension of virtual prototypes. Although certain limitations of the applied VR equipment exist, the system provides sufficient performance for educational use and product development analysis.

REFERENCES

[1] Fabrisa, C.P., Rathnera, J.A., Fonga, A.Y., Sevignya, C.P., Virtual Reality in Higher Education, International Journal of Innovation in Science and Mathematics Education, Vol. 27, No. 8, pp. 69-80, 2019.

[2] Buzjak, D., Virtual reality and its applications, bachelor thesis, University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Zagreb, 2016

[3] Seth, A., Vance, J.M. & Oliver, J.H. Virtual reality for assembly methods prototyping: a review. *Virtual Reality* Vol. **15**, pp. 5–20 (2011). https://doi.org/10.1007/s10055-009-0153-y

[4] Llanos-Ruiz, D., Abella-García, V., Ausín-Villaverde, V., Virtual Reality in Higher Education: A Systematic Review Aligned with the Sustainable Development Goals, Societies Vol.15, 251, 2025. https://doi.org/10.3390/soc15090251

[5] Palinkas, I., Desnica, E., Pekez, J., Radovanovic, LJ., Additive manufacturing and virtual or augmented reality in design for maintainability, H. Glavaš et al. (Eds.): OTO 2024, LNNS 1242, pp. 295–304, 2025. https://doi.org/10.1007/978-3-031-80597-4_24

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GRAVIMETRIC ANALYSIS OF PARTICULATE MATTER EMISSIONS FROM MILLING PROCESSES

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Abstract: The milling process is recognized as a significant source of airborne particulate matter, particularly within the inhalable and respirable fractions that pose health risks to workers and contribute to environmental pollution. This study investigates the influence of milling operations on the generation of inhalable particles and evaluates their concentration using gravimetric measurement techniques. Air samples were collected on filters with a personal sampler pump during milling operations and analyzed to determine mass concentrations and compliance with occupational exposure limits. The results indicate that particle emissions are strongly dependent on the type of material, milling speed, and tool condition. The findings highlight the importance of continuous monitoring of airborne particulate matter and the implementation of effective dust control strategies to reduce occupational exposure and improve workplace air quality.
Key words: inhalable particles, concentration, milling

INTRODUCTION

Particulate matter (PM) refers to solid or liquid particles suspended in the air, with the PM_{10} and $PM_{2.5}$ fractions being the most significant in terms of health risks and regulatory standards. The milling process, which involves the size reduction of raw materials such as metals, grains, minerals, or wood, is a well-known source of airborne dust and fine particles [1]. Emissions of particulate matter during milling can adversely affect workplace air quality, contribute to environmental pollution, and pose challenges for compliance with occupational health and safety regulations [2,3]. Understanding the characteristics and concentrations of PM generated in milling operations is therefore essential for assessing exposure risks and implementing effective control measures.

Particulate matter generated during milling originates from multiple sources. Mechanical abrasion between the material and milling tools produces dust, while cutting and grinding edges contribute to the formation of fine particles. Additional emissions arise from the handling and transport of materials within the milling facility, including loading, unloading, and conveyor movement [4]. Secondary resuspension of settled dust, caused by air currents or vibrations, further increases airborne particle concentrations. The type of material processed, milling speed, tool wear, and operational conditions significantly influence the quantity and size distribution of particulate emissions [5]. Understanding these sources is critical for designing appropriate monitoring strategies and implementing effective dust control measures to minimize occupational exposure.

In this study, we measured the inhalable fraction of particles generated during the milling process using a personal air sampler. A personal air sampler is designed to simulate the amount of particles that may enter a worker's respiratory tract during specific machining operations. Measurements were conducted on various milling machines within a company specializing in conventional milling, extrusion, simulation, rapid prototyping, as well as precision CNC milling and machining of metals and plastics for the production of small- and medium-series parts. Following the sampling phase, filters containing the collected particulate matter were analyzed gravimetrically using an analytical balance to determine particle concentrations.

MATERIAL AND METHODS

The measurements were carried out in a company specializing in CNC precision milling, metal and plastic machining, as well as the production of small- and medium-series parts. The production processes also include welding, part protection, and component assembly. In addition, the company provides services such as conventional milling, extrusion, simulation, rapid prototyping (sand/PE electrodes), 3D solid modeling, HURCO machining center operations, and Charmilles CNC electrical discharge machining.
The measurements were conducted only during the plastic milling process on a Vertical Machining Center (VMC). A VMC is a fundamental component in contemporary manufacturing, particularly in the precision machining of polymeric (plastic) materials. Defined by a vertically oriented spindle that moves along the Z-axis, the VMC is a high-speed Computer Numerical Control (CNC) machine utilized for complex operations, including milling, drilling, and tapping. Its structural rigidity and advanced control capabilities ensure the tight tolerances and smooth surface finishes required for producing intricate plastic components, prototypes, and tooling molds. The process of high-speed plastic milling inherently generates airborne particulate matter (dust). Due to the potential health risks associated with inhaling fine polymer dust, the design and operation of the VMC are critically evaluated from an occupational safety perspective. A key feature of modern industrial VMCs is the fully enclosed workspace, which serves two primary environmental and safety functions.
Dust particle sampling in engineering practice is commonly performed using time-integrated methods to determine aerosol concentration. In this approach, the sampler draws air through a pump, simulating the breathing rate of workers. Airborne particles are carried into the device with the airflow and subsequently deposited on a filter medium.
When personal sampling is applied, the device is positioned in the operator's breathing zone (approximately 20–30 cm from the nose and mouth) (Figure 1), allowing for an accurate assessment of occupational exposure. The sampler is lightweight and worn by the worker, enabling unrestricted movement during regular work activities.

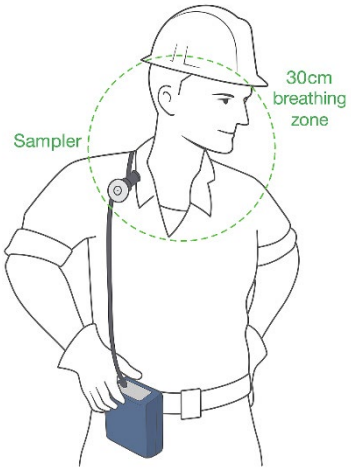


Fig. 1. *Position of a personal sampler*

In this study, sampling was conducted using a personal sampler EGO PLUS TT (Zambelli), equipped with a conical nozzle and 25 mm cellulose mixed ester filters, which are suitable for microscopic examination. The airflow was maintained at 3.5 L/min in accordance with the manufacturer's specifications. The measurements were performed during machine operation, typically lasting several hours. They were conducted at a stable room temperature of 25 °C under conditions with no air movement, and with relative humidity ranging from 40% to 43%. The sampler was positioned on the upper chest, close to the collarbone, within the worker's breathing zone.

For the determination of particle concentration by the gravimetric method, an analytical balance Kern & Sohn ABJ 120-4NM with an accuracy of ±0.0002 g was used.

RESULTS AND DISCUSSION

The analytical balance is a high-precision instrument that ensures reliable and reproducible mass determination. It is suitable for gravimetric analyses and other laboratory applications requiring fine measurement resolution (Figure 2).



Fig. 2. *The weighing scale for the gravimetric filter analysis.*

The volume of airflow through the sampler is calculated by multiplying the mean volumetric flow rate, expressed in cubic meters per minute (m³/min), by the sampling duration in minutes. (Note: the flow rate in L/min equals 1000 times the flow rate in m³/min.) The net weight of the collected particulate matter on the filter, measured in milligrams (mg), is then divided by the sampled air volume in cubic meters (m³), yielding the average particle concentration in milligrams per cubic meter of air (mg/m³) [6,7].

$$x = \frac{m_2 - m_1}{\mathrm{V}} * 1000 \quad (1)$$

where:
x – Particulate concentration [mg/m³]
m_2 – Filter mass after sampling [mg]
m_1 – Filter mass before sampling [mg]
V – Volume of sampled air, calculated as the product of the volumetric airflow rate [L/min] and the sampling duration [min], expressed in liters [L].
The VMC measurements included the assessment of two distinct scenarios during the plastic milling process:

1. Closed machine scenario
2. Open machine scenario

Emulsions were present in both cases.

Closed machine scenario
The sampling duration was 3 hours (h), and the airflow rate was 3.5 L/min. Multiplying the flow rate by the sampling duration gives a volume of 630 L. However, the EGO PLUS TT personal sampler provides data via its software as a normalized volume in "N-litres." Thus, the normalized volume of sampled air was 628.8 L for the closed machine scenario and 628.1 L for the open machine scenario.

The filter mass before sampling (m_1) was 0.0222 g, and the mass after sampling (m_2) was 0.0287 g.
The particulate concentration is calculated as:

$$x_1 = \frac{28.7 - 22.2}{628.8} * 1000 = 10.4\, mg/m^3$$

Open machine scenario
The sampling duration was 3 hours (h), and the airflow rate was 3.5 L/min. The normalized volume of sampled air was 628.1 L.
The filter mass before sampling (m_1) was 0.0222 g, and the mass after sampling (m_2) was 0.0299 g.

$$x_2 = \frac{29.9 - 22.2}{628.1} * 1000 = 12.6\, mg/m^3$$

In European Union member states, as well as in most countries adhering to EU or international standards (such as ACGIH), the general occupational exposure limit (OEL) for inhalable dust is 10 mg/m³ for an 8-hour Time-Weighted Average (TWA) [8]. The term *inhalable fraction* (or *inhalable dust*) refers to the total airborne particulate matter that can be inhaled and deposited anywhere within the respiratory tract, from the nose to the terminal bronchioles. Scientifically, this fraction consists of particles with an aerodynamic diameter of up to approximately 100 µm.

CONCLUSION

The enclosure facilitates the efficient operation of local exhaust ventilation (LEV) or aspiration systems, effectively capturing plastic dust and chips at the source and preventing their dispersal into the ambient air.
When assessing occupational exposure, a critical distinction must be made between the machine's operational states. Measurements taken with the VMC enclosure closed represent the standard, controlled exposure level during routine operation, reflecting the protective efficacy of the machine's integrated safety features. Conversely, measurements taken with the enclosure open—for example, during material setup, monitoring, or maintenance—represent a worst-case scenario or maximum potential exposure.
The results confirm the protective efficacy of the machine's enclosure and integrated safety systems. The closed machine scenario resulted in a particulate concentration of 10.4 mg/m³, while the open machine scenario yielded a significantly higher concentration of 12.6 mg/m³. This difference (≈21% increase) clearly demonstrates that opening the machine's doors or guards directly results in a worst-case exposure scenario, allowing greater dispersal of plastic dust and chips into the ambient air, despite the continued presence of emulsions in both cases. However, it is critical to note that both measured concentrations—10.4 mg/m³ (closed) and 12.6 mg/m³ (open)—exceed the permissible occupational exposure limit (OEL) of 10 mg/m³ (8-h TWA). Measurements were conducted over a 3-hour period during active machine operation, not averaged across a full 8-hour shift. This methodological difference likely influenced the reported concentrations, since OEL values are defined for an 8-hour time-weighted average exposure. Importantly, the measurements did not take into account the use of personal protective equipment (PPE), which, based on the results, must be considered mandatory in this working environment. Furthermore, the presence of dispersed emulsion droplets during machining may have contributed to additional loading of the sampled filters, potentially influencing the gravimetric results.
In summary, the enclosure is essential for reducing exposure during the plastic milling process, but on its own it is insufficient to ensure compliance with occupational exposure limits. Continuous monitoring, the mandatory use of PPE, consideration of full-shift exposure

durations, and the implementation of enhanced dust control strategies are therefore necessary to safeguard worker health.

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REFERENCES

[1] Choisez, L., Stevens, N., Prasidha, W., Kuypers, B., Mauxion, T., de Goey, P., Finotello, G., Jacques, J. On the use of industrial steel mill scale as a high-density energy carrier: Part I. Reaction processes and particle size evolution over cycling, Fuel, Vol. 405, 2026, Article in press.
[2] Yang, Q., Liu, G., Falandysz, J., Yang, L., Zhao, C., Chen, C., Sun, Y., Zheng, M., Jiang, G. Atmospheric emissions of particulate matter-bound heavy metals from industrial sources, Science of The Total Environment, Vol. 947, 2024.
[3] Reis, R., Kokare, S., Oliveira, J.P., Matias,J., Godina, R. Life cycle assessment of metal products: A comparison between wire arc additive manufacturing and CNC milling, Advances in Industrial and Manufacturing Engineering, Vol. 6, 2023.
[4] Zhang, H., Sun, W., Li, W., Wang, Y. Physical and chemical characterization of fugitive particulate matter emissions of the iron and steel industry, Atmospheric Pollution Research, Vol. 13, Issue 1, 2022.
[5] Shin, H., Jeong, S., Hong, J., Wi, E., Park, E., Yang, S., Kwon, J., Lee, H., Lee, J., Kim, Y. Rapid generation of aged tire-wear particles using dry-, wet-, and cryo-milling for ecotoxicity testing, Environmental Pollution, Vol. 330, 2023.
[6] American Industrial Hygiene Association (AIHA), Publishes manuals on the use of direct-reading instruments: Direct-Reading Instrumental Methods for Gases, Vapors, and Aerosols, 2013.
[7] Health and Safety Executive, Methods for the Determination of Hazardous Substances MDHS14/3: General methods for sampling and gravimetric analysis of respirable and inhalable dust, 2000.
[8] Directive 2009/161/EU - indicative occupational exposure limit values



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THE ROLE AND IMPORTANCE OF CONDENSATE PUMPS IN THE OPERATION OF A 110 MW COMBINED HEAT AND POWER PLANT

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Abstract: This paper analyzes the design, function, and operation of the condensate pumps I0 and II0 within the thermal power and heating plant (CHP) with a nominal electric capacity of 110 MW and a thermal output for district heating of 140 MWt. The facility is designed for the combined production of electricity and heat. The I0 condensate pumps, vertical multistage centrifugal units, ensure continuous circulation of condensate from the turbine condenser through the regenerative heating system and return the condensate to the deaeration tanks. The II0 condensate pumps, horizontal multistage centrifugal units, play a critical role during system startup phases and in the transfer of feedwater between tanks of varying pressure levels. The study presents the technical parameters of these pumps, describes startup modes and automatic control systems, and emphasizes their importance for the safe, efficient, and continuous operation of the plant. Based on pipeline diagrams, hydraulic losses and the required pump efforts under different operating conditions are analyzed. The conclusion highlights the significance of proper sizing, control, and maintenance of condensate pumps to ensure the reliable operation of the entire thermal energy system.
Key words: condensate pump, thermal power plant, CHP, centrifugal pump, condenser, feedwater, energy system

INTRODUCTION

Combined heat and power plants (CHP) represent key energy systems that enable the simultaneous production of thermal and electrical energy within a single integrated process, thereby achieving high energy efficiency and rational fuel utilization. In modern energy facilities, particularly those designed for district heating in urban areas, the reliable operation of auxiliary systems is of critical importance, with condensate pumps playing a particularly prominent role [1, 2].

Condensate pumps, as components of the condensation system in thermal power facilities, are responsible for collecting condensate from the turbine condenser and transporting it through regenerative heating devices to the deaeration system. This enables a closed-loop feedwater cycle, which reduces energy losses and enhances operational safety [2, 4]. In the facility under study, two groups of condensate pumps are employed: vertical condensate pumps (I0), which operate in continuous condensate circulation mode, and horizontal condensate pumps (II0), which play a crucial role during plant startup and in supplying feedwater to the boilers [1, 5].

This paper focuses on the analysis of their design, technical characteristics, operating principles, and functional significance within the overall thermal energy process. Special attention is given to the hydraulic characteristics of the system, automation in operation, and the importance of regular monitoring in order to ensure the optimal and uninterrupted functionality of the CHP system [6, 7].

MATERIAL AND METHODS

The analysis presented in this paper is based on the technical documentation and the actual configuration of a Combined Heat and Power (CHP) plant with a nominal electrical capacity of 110 MW, designed for the cogeneration of electricity and heat [8]. Special attention is given to the I0 and II0 condensate pumps, which are essential components for condensate circulation and for ensuring the reliable operation of the boiler feedwater system.

The methodological approach is structured through the following steps:

- Technical analysis of pump construction – Performed based on manufacturer documentation and specifications of the installed units.
- Analysis of operating modes and automation – Involves evaluation of startup logic, minimum and maximum flow rates, system pressures, and activation of backup pumps, along with the interpretation of the operation of electrical fittings and control valves.
- Hydraulic analysis – The characteristics of the discharge pipelines for both condensate pump systems were examined, including elevation differences, pressure drops, static head variations, and required control resistances.
- Operational monitoring and control parameters – Includes analysis of parameters monitored in real time by the operating personnel.

The application of these methods enables a systematic assessment of the efficiency, reliability, and energy-related role of condensate pumps within the overall CHP process.

I0 Condensate Pumps

The I0 condensate pumps (Fig. 1) represent key components of the condensate circulation system in the CHP plant. These are vertical, multistage centrifugal pumps of the type 125-CJAV-265-15/7-LU-OO-F, equipped with radial impellers. The main technical specifications of each pump are presented in Table 1 [8].



Fig. 1. *I0 Condensate Pumps*

The primary function of these pumps is to extract condensate from the turbine condenser and convey it through the low-pressure regenerative heating system, which includes the gland steam condenser, the small consumers' steam condenser, and the low-pressure heaters of stages I and II. The system includes three I0 condensate pumps, two of which operate under normal conditions while the third serves as a standby unit. The pumps are directly connected to the turbine condenser, and their total capacity corresponds to the maximum steam inflow under full condensation mode.
To ensure operational stability, the system is designed so that the minimum condensate flow is maintained via recirculation back to the condenser, while water is also delivered from the pump discharge to cooling and sealing systems. The pump startup process requires the condensate level in the condenser to reach at least one-third of its volume, which is automatically regulated via a control valve on the discharge line.
The pump startup sequence involves the following steps:

1. The selected pump is activated with the shut-off electro valves in the closed position.
2. After a 30-second delay, both the shut-off valve and the control valve on the minimum condensate recirculation line are opened. This enables partial flow return to the condenser, ensuring stable cooling of the gland steam condenser and the small consumers' condenser with a minimum flow of 80 t/h.
3. Upon reaching a discharge pipeline pressure of 0.8 MPa, the valves to the main line are opened, while the minimum flow recirculation line is gradually closed.
4. When the condensate flow reaches 90 t/h, the second pump is automatically activated, and if it exceeds 170 t/h, the third (standby) pump is also engaged.
5. Conversely, when the flow drops below 155 t/h, the third pump is deactivated, and if it falls further below 80 t/h, only one pump remains in operation.

During pump operation, continuous monitoring of key parameters is performed:
- System sealing and cooling water temperature (the outlet temperature is allowed to be 10–15 °C higher than the inlet),
- Lubrication and bearing temperatures (must not exceed 75 °C),
- Motor temperature and load (monitored via amperage),
- Drive power increase, which may indicate increased flow or mechanical irregularities,
- Condensate level in the collector,
- Minimum flow through the gland steam and small consumers' condensers (≥ 80 t/h).

Table 1. *Technical Characteristics of I0 Condensate Pumps*

Parameter	Value
Pump type	125-CJAV-265-15/7-LU-OO-F
Pump configuration	Vertical, centrifugal, multistage
Impeller type	Radial
Number of installed pumps	3 (two operational + one standby)
Flow rate	125 m³/h
Head (specific energy)	1334 J/kg
Motor power	70 kW
Motor speed	1470 rpm
Minimum condensate level required for startup	1/3 of condenser height
Minimum flow required for condenser cooling	80 t/h
Activation of second pump	When flow reaches 90 t/h
Activation of third (standby) pump	When flow reaches 170 t/h
Deactivation of third pump	When flow drops below 155 t/h
Deactivation of second pump	When flow drops below 80 t/h
Maximum permissible bearing temperature	75 °C
Allowable increase in cooling water temperature	10–15 °C compared to inlet temperature

II0 Condensate Pumps

The II0 condensate pumps are horizontal, multistage centrifugal units of type 250-CHT-350-48/3-OU-00-F/2E. These pumps are essential for the recirculation and transfer of feedwater between tanks operating at different pressures within the thermal power cycle. The main technical characteristics of the pumps are presented in Table 2.
During cold startup of the thermal plant, the II0 condensate pumps enable circulation of feedwater from the low-pressure tank via the auxiliary line. This recirculation continues until the required feedwater temperature in the system is achieved.
Under normal operating conditions, the II0 condensate pumps transfer water from the low-pressure tank (temperature up to 140 °C, pressure 0.4 MPa) to high-pressure tanks, which then supply the boilers. These pumps are also used to fill boiler units prior to block startup, using the same discharge and auxiliary lines.

Typically, two condensate pumps are in operation, while the third serves as a standby and is automatically activated if needed. The startup sequence of a pump begins with the control valve on the discharge pipeline in a closed position. After a brief delay, the shut-off electrovalve on the minimum flow recirculation line opens, allowing the return of condensate to the low-pressure tank. Once the discharge pressure reaches 0.8 MPa, the shut-off and control valves toward the main line open sequentially.
During pump operation, continuous monitoring and control of the following parameters is essential:

- Equipment functionality and sealing integrity
- Bearing temperature (maximum allowed: 75 °C) and lubrication
- Pressure and temperature at the pump discharge
- Activation of the standby pump when flow exceeds approximately 340 t/h
- Deactivation of the standby pump when flow drops below 290 t/h
- Activation of the recirculation loop when flow falls below 86 t/h, triggering closure of electrovalves to the main line and return of water to the low-pressure tank

Figure 2 illustrates the actual configuration of the II0 condensate pumps [8]..

Table 2. *Technical Characteristics of II0 Condensate Pumps*

Parameter	**Value**
Pump type	250-CHT-350-48/3-OU-00-F/2E
Manufacturer	SIGMA Lutin, Czech Republic
Pump configuration	Horizontal, multistage, centrifugal
Number of installed pumps	3 (two operational + one standby)
Flow rate	317.5 m³/h
Head (specific energy)	870 J/kg
Motor power	121 kW
Motor speed	1480 rpm
Working fluid	Feedwater (up to 140 °C, 0.4 MPa)
Function during cold startup	Recirculation from the low-pressure tank via line NB02
Function during normal operation	Transfer to the high-pressure tank and boiler filling
Activation of standby pump	At flow rate ≥ 340 t/h
Deactivation of standby pump	At flow rate ≤ 290 t/h
Activation of recirculation (minimum flow)	At flow rate ≤ 86 t/h
Maximum permissible bearing temperature	75 °C
Startup parameter (discharge pressure for valve opening)	≥ 0.8 MPa



Fig. 2. *II0 Condensate Pumps*

RESULTS AND DISCUSSION

The analysis of the operation of I0 and II0 condensate pumps within the 110 MW Combined Heat and Power (CHP) plant indicates that these units play a critical role in maintaining continuous condensate flow and ensuring the stable operation of the feedwater and boiler sections of the system.

The I0 condensate pumps, designed as vertical multistage centrifugal units, facilitate efficient condensate recirculation from the turbine condenser through the low-pressure regenerative heaters. Their automatic operation, based on condensate quantity and system pressure, enables the dynamic inclusion of additional pumps when needed. This ensures optimal condenser cooling and prevents thermal stress in the system. The minimum required flow for safe condenser cooling (80 t/h) is reliably maintained through the minimum recirculation system, even under variable turbine operating conditions. Notably, the automated startup sequence and pump control eliminate the need for manual intervention, significantly improving operational safety.

The horizontally configured II0 condensate pumps prove essential during the cold startup phase, providing recirculation and thermal conditioning of feedwater in the low-pressure tank via the auxiliary line. Under normal operating conditions, they transfer water to the high-pressure tank and enable boiler filling prior to turbine engagement. Full automation is also implemented here—the standby pump is activated or deactivated depending on flow thresholds (≥ 340 t/h and ≤ 290 t/h). In the event of a critical flow drop, the system automatically switches to minimum recirculation mode, protecting the equipment from potential damage.

For the selected pipeline route from the condenser to the deaerator in the low-pressure tank, a characteristic pipeline curve was developed and analyzed, taking into account all hydraulic resistances. This enables precise estimation of the required pump head under real operating conditions (Fig. 3).

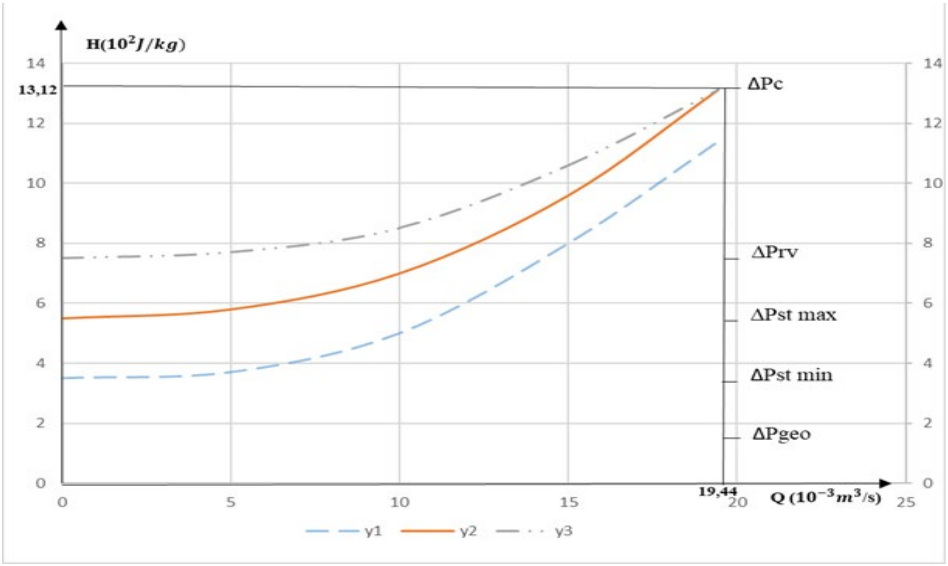


Fig.3. *Discharge Pipeline Characteristics of First-Stage Condensate Pumps*

y1 – Minimum pressure at deaerator; y2 – Flow through the deaerator proportional to pump flow; y3 – Maximum flow through the deaerator
ΔPgeo (bar) – Difference in geodetic elevation
ΔPst (bar) – Difference in static pressure
ΔPrv (bar) – Minimum pressure drop across the control valve
ΔPc (bar) – Pressure drop in the pipeline

Figure 4 shows the pipeline curve for the feedwater route from the low-pressure to the high-pressure tank. This diagram provides insight into the system's hydraulic resistance and enables precise sizing of pumps and control equipment.

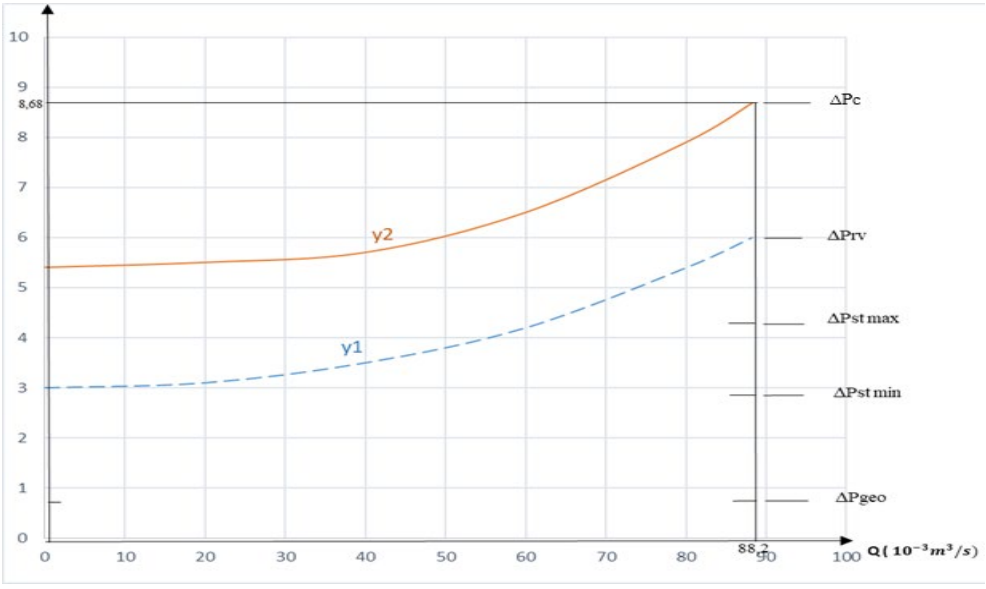


Fig 4. *Discharge Pipeline Characteristic Curve for Second-Stage Condensate Pumps*

y1 – Minimum pressure in the deaerator
y2 – Maximum pressure in the deaerator
ΔPgeo (bar) – Geodetic elevation difference
ΔPst (bar) – Static pressure difference

∆Prv – Minimum pressure drop across the control valve
∆Pc (bar) – Pressure drop in the pipeline

The characteristic pipeline curves analyzed for both pump groups confirm that all hydraulic resistances, elevation differences, and pressure drops were adequately considered during system design. This results in optimal pump sizing and balanced load distribution across all active units.
In conclusion, the performance of the I0 and II0 condensate pumps in the CHP plant demonstrates high reliability and efficiency. The automation system, together with the technical pump configuration, ensures stable condensate transfer, flexible operating regimes, and protection of critical components. Such a solution significantly enhances the overall energy efficiency and operational safety of the thermal power unit. Fig. 5 presents a graph illustrating pump activation as a function of condensate flow.

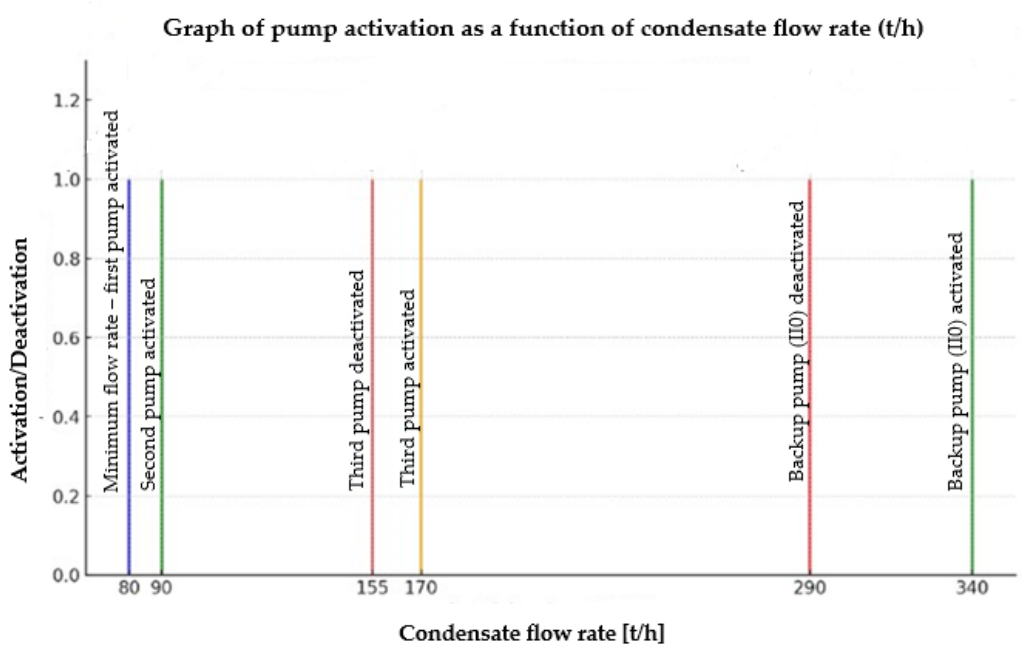


***Fig. 5**. Pump activation graph as a function of condensate flow rate.*

CONCLUSION

Condensate pumps constitute a critical component of the condensate circulation system in thermal power plants, directly impacting the efficiency, safety, and operational continuity of the entire plant unit. The analysis of the operation of pumps I0 and II0 within the Combined Heat and Power Plant (CHP) demonstrated that they are functionally, technically, and hydraulically well integrated into the process of thermal and electrical energy production.
The vertical condensate pumps I0 ensure a stable flow of condensate through the regenerative section of the system, enabling optimal heat utilization and the return of condensate into the cycle. Their automation and recirculation system allow adaptation to variable turbine operating regimes, thereby enhancing the overall system reliability. Conversely, the horizontal condensate pumps II0 play a crucial role during plant startup phases and in the distribution of feedwater between reservoirs at different pressure levels, including boiler filling prior to startup.
The implementation of automated start-stop regimes, along with precise flow and pressure regulation, ensures that pump operation is fully synchronized with plant demands, eliminating

the need for manual adjustments. This approach contributes to a high degree of operational safety and minimizes the risk of potential downtime [3, 9].
In conclusion, a properly designed and managed condensate pump system is essential for the efficient and reliable operation of combined heat and power plants. The experience gained at the CHP plant can serve as a model of best practice in the design and management of auxiliary systems within modern thermal power facilities.

REFERENCES

[1] Lian, Y., He, Z., Ma, G., Structural resonance analysis and treatment of large thermal power unit vertical condensate pump variable frequency operation, Proceedings of SPIE the International Society for Optical Engineering, vol. 13163, 1316318, 2024.
[2] Wang, X., Qu, Q., Application of Variable Frequency Decoupling Control for Condensate Pump of 1 000 MW Units in Energy Saving Reconstruction, Zhejiang Electric Power, vol. 40, no. 2, pp. 112–118, 2021.
[3] Melgarejo-Jara, M., Chamorro-Atalaya, O., Aldana-Trejo, F., Zevallos-Vera, E., Anicama-Navarrete, E., Automated drainage system for thermoelectric power plant, Indonesian Journal of Electrical Engineering and Computer Science, vol. 29, no. 3, pp. 1393–1401, 2023.
[4] Kumar, R., Thermodynamic modeling and validation of a 210-MW capacity coal-fired power plant, Iranian Journal of Science and Technology Transactions of Mechanical Engineering, vol. 40, no. 3, pp. 233–242, 2016.
[5] Kurien, C., Srivastava, A.K., Case study on the effectiveness of condition monitoring techniques for fault diagnosis of pumps in thermal power plant, Mechanics and Mechanical Engineering, vol. 23, no. 1, pp. 70–75, 2019.
[6] Sterligov, V.V., Pulikov, P.S.,Thermodynamic resource of increasing energy efficiency of steam power plants, Izvestiya Ferrous Metallurgy, vol. 63, no. 2, pp. 102–107, 2020.
[7] Qin, H., Jin, J., Ni, H., Simulation analysis on startup period of condensate pump considering impact of high temperature water leaking, Harbin Gongye Daxue Xuebao Journal of Harbin Institute of Technology, vol. 52, no. 1, pp. 118–125, 2020.
[8] Project-Technical Documentation of CHP Zrenjanin, Pumps, accessed on October 17, 2024.
[9] Malik, S., Tewari, P.C., Performance modeling and maintenance priorities decision for the water flow system of a coal-based thermal power plant, International Journal of Quality and Reliability Management, vol. 35, no. 4, pp. 996–1010, 2018.

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BEST AVAILABLE TECHNOLOGIES AND PRACTICES TO TREAT THE THERMAL SPA WASTEWATER

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Abstract: The reuse of treated thermal wastewater from spas offers an innovative and sustainable approach to the restoration of degraded soda pan ecosystems. These unique saline-alkaline habitats are highly sensitive to changes in hydrology, salinity, and temperature, and their conservation requires carefully tailored interventions. Advanced treatment technologies enable the purification of thermal wastewater to meet the specific ecological requirements of soda pans. Carefully integrated, the reuse of spa wastewater can improve habitat quality, support rare and endemic species, and contribute to the long-term resilience and conservation of soda pans. This approach represents a promising model for combining sustainable water management with biodiversity restoration in vulnerable ecosystems.
Key words: reuse, thermal, wastewater, treatment, soda pan

INTRODUCTION

Thermal wastewater originating from spas and related facilities represents both an environmental challenge and an underutilized resource. When discharged untreated, such effluents can disrupt local ecosystems due to elevated temperature, altered salinity, and imbalanced chemical composition. However, with the application of advanced treatment technologies, thermal wastewater can be transformed into a valuable input for ecological restoration projects, particularly for fragile saline-alkaline habitats such as soda pans.
Recent technological developments, most notably low-temperature desalination, membrane-based separation processes, and systems with integrated waste heat recovery, enable energy-efficient purification of thermal wastewater. By selectively managing salinity and pH, recovering useful minerals, and regulating discharge temperature, it is possible to tailor the treated water to meet the ecological requirements of degraded habitats.
Beyond the ecological benefits, such approaches contribute to broader sustainability goals by lowering freshwater demand, reducing greenhouse gas emissions, and minimizing operational costs in industrial and spa sectors. Furthermore, adaptive water management strategies, combined with habitat enhancement measures and continuous ecological monitoring, provide safeguards to ensure long-term success.
This paper explores the potential of reusing treated thermal wastewater for the restoration of degraded soda pan ecosystems, with a focus on aligning technological capabilities with ecological needs. Special attention is given to water quality optimization, temperature regulation, hydrological management, and biodiversity support, as well as the role of scientific partnerships and pilot-scale demonstrations in scaling up best practices.

MATERIAL AND METHODS

Desalination¶

Thermal Desalination Technologies for Reuse of Spa and Industrial Wastewater
Thermal wastewater from spas and industrial facilities can be treated and reused through advanced thermal desalination technologies, offering sustainable solutions for water scarcity and ecological restoration. Key methods include Multi-Stage Flash (MSF) distillation, Multi-Effect Distillation (MED), Mechanical Vapor Recompression (MVR), and Low-Temperature Thermal Desalination (LTTD). Each technology has unique advantages and limitations depending on energy availability, feedwater quality, and operational scale.

Multi-Stage Flash (MSF) Distillation

MSF involves heating saline water and flashing it into steam across multiple stages with progressively lower pressures. Each stage recovers heat from condensed vapor to preheat incoming feedwater, improving energy utilization. MSF systems are robust, capable of handling high-salinity water, and suitable for large-scale centralized plants, often integrated with cogeneration or waste heat systems [1,2]. However, MSF is energy-intensive, prone to scaling and corrosion, and requires significant pretreatment, making it less favorable for smaller spa facilities or mineral-rich thermal water.

Multi-Effect Distillation (MED)

MED improves on MSF by cascading vapor from one stage to the next, enhancing thermal efficiency and reducing scaling risks. Operating typically at lower top brine temperatures (60–70°C), MED is compatible with low-grade or waste heat and renewable energy sources [3]. It is suitable for medium to large-scale operations (5,000–30,000 m³/day) and increasingly favored over MSF due to lower energy consumption, greater feedwater tolerance, and modular scalability. Pretreatment remains necessary for mineral-rich thermal waters to maintain efficiency.

Mechanical Vapor Recompression (MVR)

MVR recycles the latent heat of vapor by mechanically compressing the evaporated vapor and reusing it to heat incoming water, drastically reducing external energy needs. It can achieve desalination rates up to 99.66% and water recovery up to 85% [4]. MVR systems are compact, energy-efficient, and suitable for high-salinity or scaling-prone waters, making them relevant for closed-loop spa wastewater reuse and ecological restoration. Limitations include high capital costs, maintenance requirements, and sensitivity to water composition variations.

Low-Temperature Thermal Desalination (LTTD)

LTTD operates under near-vacuum conditions, allowing water to evaporate at ambient temperatures and condense using cold water sources, such as deep seawater or cooling systems. It is energy-efficient, environmentally sustainable, and has minimal scaling and corrosion issues [5,6]. LTTD is particularly suitable for small- to medium-scale applications, island communities, or remote areas where conventional methods are energy-intensive. Its main limitation is site specificity, requiring access to temperature gradients between warm surface water and cold deep water.

Selective Ion Management

Thermal Membrane Desalination for Spa and Industrial Wastewater Reuse

Thermal Membrane Distillation (TMD) combines thermal evaporation with membrane separation, allowing only water vapor to pass through a hydrophobic membrane while retaining salts and non-volatile contaminants. Operating at relatively low temperatures (40–80°C), TMD is energy-efficient and compatible with low-grade or residual heat, making it suitable for industrial wastewater, high-salinity brines, and spa effluents [7,8].

Four main TMD configurations are commonly used:

- Direct Contact Membrane Distillation (DCMD): Simple, feed and permeate directly contact the membrane.
- Air Gap Membrane Distillation (AGMD): Includes an air gap to reduce heat loss, increasing thermal efficiency.
- Vacuum Membrane Distillation (VMD): A vacuum on the permeate side enhances vapor transport and reduces temperature requirements.

Sweeping Gas Membrane Distillation (SGMD): Uses an inert gas to carry vapor to an external condenser. TMD achieves high rejection of salts, heavy metals, and organics (>99%), operates at low pressures, and has a modular design suitable for decentralized or industrial deployment. It is especially relevant for environmentally sensitive applications such as soda pan restoration, wetland revitalization, and industrial symbiosis. Limitations include relatively low water flux compared to reverse osmosis, requirement of thermal energy, and potential membrane fouling without pretreatment.

Vacuum Membrane Distillation (VMD)
VMD is a TMD variant where the permeate side is under vacuum, enhancing vapor transport and water flux. Water is heated to moderate temperatures (50–80 °C) and evaporates across a hydrophobic membrane, while salts and non-volatiles remain in the feed. Vapor is condensed externally, yielding high-purity water with salt rejection >99.9% [9].
Advantages of VMD include:

- High water flux due to strong vapor pressure gradients.
- Operation at low feed temperatures, enabling use of solar or waste heat.
- Compact and scalable systems suitable for modular deployment.
- Ideal for Zero Liquid Discharge (ZLD) and concentration of hypersaline brines.

Challenges include membrane wetting risk with surfactants or organics, the need for vacuum pumps and external condensers, and potential scaling or fouling from untreated feedwater. Despite these, VMD is effective for seawater and brackish water desalination, industrial brine treatment, high-salinity wastewater recovery, and integration into hybrid systems.

Temperature Adjustment
Soda pans are ecologically sensitive saline-alkaline wetlands, hosting unique microorganisms, crustaceans, and birds. Discharges of warm industrial or municipal wastewater can disrupt microbial communities, reduce oxygen solubility, and alter seasonal reproductive cycles, threatening biodiversity. Temperature regulation prior to discharge is therefore essential.
Passive Heat Exchangers
Passive systems transfer heat without mechanical energy, using ambient air, soil, or water. Common types include buried pipe systems, air-cooled radiators, and submerged coils [10].
Advantages of the systems include its energy efficiency, low maintenance requirements, environmental friendliness, cost-effectiveness for small to medium flow rates, and silent operation. However, the systems also present certain disadvantages, such as limited cooling capacity, variability in seasonal efficiency, substantial space requirements, slow cooling processes, and challenges associated with retrofitting [11].
Cooling Ponds and Constructed Wetlands
These nature-based solutions slow water flow, allowing heat dissipation via radiation, convection, and evaporation. Constructed wetlands additionally filter nutrients and improve water quality [12,13]. Advantages include low energy consumption, multifunctionality, enhancement of biodiversity, resilience, and long-term cost-effectiveness. However, the system also presents certain disadvantages, such as substantial land requirements, variability in performance due to seasonal changes, risks associated with mosquitoes and odors, sediment accumulation, and slow hydraulic throughput.
Mechanical Cooling Systems
Active systems, including cooling towers, chillers, and forced-circulation heat exchangers, provide precise temperature control for high-volume discharges. Advantages of the system include its high cooling efficiency, compact design, reliability, scalability, and automated operation. However, it also presents certain disadvantages, such as high energy and maintenance costs, noise generation, potential refrigerant leaks, and technical complexity.
Integration with Desalination and Hybrid Systems
Waste heat from industrial or power generation facilities can be used to drive thermal desalination (e.g., MED, TMD) to reduce freshwater demand and carbon footprint [11]. Hybrid systems combining Adsorption Desalination (AD) with MED enhance energy efficiency, freshwater output, and reduce environmental impact [14].
Cooling Tower Blowdown Treatment and Low-Temperature Distillation (LTD)
Blowdown water contains high salinity and impurities. Treating it with TMD, LTD, or MED allows reuse as makeup water, supporting Zero Liquid Discharge (ZLD) goals and water conservation. LTD operates under low pressure and temperature, using waste heat, achieving 80–95% water recovery with low scaling and fouling risks. Advantages include the

utilization of waste heat, high water recovery rates, environmental sustainability, and the potential for modular and scalable implementation. However, the system is associated with several disadvantages, such as high capital costs, slow processing rates, the necessity for vacuum conditions, challenges in saline concentrate disposal, and reliance on thermal energy sources [11].

DISCUSSION

The restoration and conservation of soda pan ecosystems require a careful balance between wastewater reuse and ecological protection. Treated thermal wastewater from spas represents a potentially valuable resource, but improper management can cause thermal shock, salinity shifts, or nutrient imbalances, threatening microbial communities, invertebrates, and bird populations. The discussion highlights three critical aspects: desalination technology selection, selective ion management, and temperature adjustment.

Desalination Technology Selection

Among thermal desalination options, MED and LTTD are the most suitable where low-grade or waste heat is accessible. These systems operate at lower temperatures, reduce scaling potential, and maintain water chemistry compatible with sensitive habitats. MVR offers high water recovery and low specific energy consumption but requires technical expertise and higher capital investment, making it most appropriate for industrial-scale operations. MSF, though mechanically robust, is energy-intensive and generally reserved for large-scale centralized plants with abundant thermal energy. For small to medium-scale applications or decentralized sites, thermal membrane technologies (TMD, VMD) provide additional flexibility. TMD is simpler and energy-efficient, suitable for rural or off-grid scenarios, while VMD achieves higher flux and recovery rates, ideal for industrial wastewater treatment with high-salinity streams.

Selective Ion Management

Maintaining chemical integrity is crucial for the survival of soda pan biota. Desalination and membrane processes allow for selective removal of harmful ions (e.g., sulfates, heavy metals) while retaining essential ions such as carbonates and bicarbonates. This preserves the natural mineral composition, supporting halophilic microorganisms and nutrient cycles necessary for ecological function. Continuous monitoring of water chemistry, including salinity, pH, nutrients, and trace metals, is critical to detect deviations and prevent long-term ecosystem disruption.

Temperature Adjustment

Thermal regulation is equally essential. Passive heat exchangers provide low-energy cooling suitable for small to medium flows, while constructed wetlands and cooling ponds offer multifunctional solutions that combine thermal control with water quality improvement and biodiversity enhancement. Mechanical cooling systems ensure precise temperature control in high-volume industrial discharges but come with high energy and maintenance costs. A combined or site-specific approach is recommended, matching system selection to flow rate, thermal load, ecological sensitivity, and spatial constraints. Gradual, controlled water introduction simulates natural hydrological cycles, reducing stress on biota and allowing ecosystems to adapt to new salinity and temperature regimes.

Integrated Management and Ecological Considerations

Using residual heat strategically can enhance ecological restoration. Moderately elevated temperatures during colder months maintain microbial activity and support early vegetation and zooplankton growth, benefiting higher trophic levels. Habitat design, including shallow basins, uneven bottoms, and surrounding halophytic vegetation, fosters diverse microhabitats, natural filtration, and soil stabilization. Pilot projects are essential to validate restoration strategies, monitor species response, and refine techniques prior to large-scale application. Long-term biodiversity monitoring ensures adaptive management, allowing intervention if harmful substances accumulate or ecosystem health declines.

CONCLUSION

Properly treated thermal wastewater from spas can serve as a valuable and sustainable resource for restoring soda pan ecosystems, but its successful integration requires careful consideration of both technological and ecological factors. Choosing the right desalination technology, whether MED, LTTD, MVR, TMD, or VMD, depends on site-specific conditions, energy availability, and scale, while maintaining the chemical integrity of the water through selective ion management is crucial for supporting the specialized organisms that inhabit these sensitive wetlands. Temperature regulation, achieved through passive, nature-based, or mechanical systems, prevents thermal stress and allows ecosystems to adjust gradually, supporting natural biological processes and seasonal cycles. Thoughtful habitat design and adaptive water management further enhance biodiversity and ecological resilience. Continuous monitoring and collaboration with scientific institutions ensure that restoration efforts remain responsive to environmental changes, while the integration of residual heat and renewable energy supports sustainability and resource efficiency. Overall, a holistic, carefully managed approach can restore and preserve soda pans effectively, demonstrating how technological solutions and ecological principles can work together to protect fragile saline-alkaline wetlands.

ACKNOWLEDGEMENT

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REFERENCES

[1] Shatat, M., Riffat, S.B., Water desalination technologies utilizing conventional and renewable energy sources – A review, International Journal of Environmental Science and Technology, Vol.11, No.3, pp. 379–394, 2014.
[2] Al-Karaghouli, A., Kazmerski, L.L., Water Resources and the Environment, Renewable and Sustainable Energy Reviews, Desalination, No.24, pp. 343–356, 2013.
[3] El-Dessouky, H.T., Ettouney, H.M., Fundamentals of Salt Water Desalination. Elsevier, 2002.
[4] Guo, L., Xie, Y., Sun, W., Xu, Y., Sun, Y., Research Progress of High-Salinity Wastewater Treatment Technology, Water, Vol.15, No.4, p. 684.
[5] Malshe, M., Jaiswal, A., Chavan, S., Low temperature thermal desalination using waste heat and deep sea cold water, Desalination, Vol. 205, No.1-3, pp. 231–236, 2007.
[6] Gude, V. G., Nirmalakhandan, N., Deng, S., Desalination at low temperatures using thermal energy sources, Renewable and Sustainable Energy Reviews, Vol.13, No.10, pp. 2383 2396, 2009.
[7] Khayet, M., Matsuura, T., Membrane Distillation: Principles and Applications. Elsevier, 2011.
[8] Jiaze, M., Hafiz, M. I., Yufei, W., Xiao, F., Dongmei, X., Recovering Wastewater in a Cooling Water System with Thermal Membrane Distillation, Industrial & Engineering Chemistry Research, Vol.57, No.31, pp. 10491-10499, 2018.

[9] Sharan, P., Yoon, T.J., Thakkar, H., Currier, R.P., Singh, R., Findikoglu, A.T., Optimal design of multi-stage vacuum membrane distillation and integration with supercritical water desalination for improved zero liquid discharge desalination, Journal of Cleaner Production, Vol. 361,p. 132189, 2022.
[10] Eswiasi, A., Mukhopadhyaya, P., Critical Review on Efficiency of Ground Heat Exchangers in Heat Pump Systems, Clean Technologies, Vol.2, No. 2, pp. 204-224, 2020.
[11] Shahzad, M. W., Thu, K., Kim, Y. D., Ng, K. C., An innovative approach for simultaneous fresh water production and heat recovery using hybrid MED–AD cycle, Applied Energy, Vol.187, pp.595–609, 2017.
[12] Vymazal, J. (Ed.), Transformations of nutrients in natural and constructed wetlands, Backhuys Publishers, Leiden, The Netherlands, pp. 1-93, 2001.
[13] UNEP, Waste Heat Recovery and Reuse in Water-Intensive Industries. United Nations Environment Programme, 2019.
[14] Amy, G., Ghaffour, N., Li, Z., Francis, L., Linare, R. V., Missimer, T., Lattemann, S., Membrane-based seawater desalination: Present and future prospects, Desalination, Vol. 401, pp. 16–21, 2017.

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APPLICATION OF PID CONTROLLER AND FUZZY LOGIC IN CONTROLLING A CIRCULATION PUMP

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Abstract: This paper presents comparison of proportional–integral–derivative (PID) controller and Fuzzy logic controller applied on control of circulation pump. Their comparative advantages and limitations are analyzed as well as the possibilities of integrating both approaches in real industrial conditions. The experimental model was implemented on an ABB controller where a circulation pump for filling the tank was used as an actuator. The aim of the paper is to evaluate the performance of both controllers through the criteria that the same amount of time is used for tuning of the parameters of both controllers.
Key words: Control, volume, flow

INTRODUCTION

In modern industrial processes, precise and efficient control is a basic requirement for system stability and reliability. A special challenge arises in nonlinear systems and systems with variable parameters, where traditional approaches, such as proportional–integral–derivative (PID) control, cannot always provide satisfactory performance. The PID controller although dominant in the field of automatic control for decades due to its simple implementation and fast tuning, shows limitations in complex and dynamic environments. On the other hand, Fuzzy controllers offer a more flexible approach, based on the principles of human reasoning and the use of linguistic variables. Their advantage is reflected in the ability to process imprecise and uncertain information, which makes them more suitable for controlling systems with pronounced nonlinearity. However, their implementation requires more complex parameter settings and definition of rules, which prolongs the development process.

METHODOLOGY

The subject of this research is the analysis and comparison of PID and Fuzzy controllers in real conditions, when controlling a circulation pump intended for tank refilling. The implementation of both controllers was performed on an ABB PLC (model PM5052-T-ETH), [1] in the Automation Builder development environment, which allows programming in different languages (ST, FBD, LD, SFC, CFC), as well as visualization and simulation of the system, [2]. The goal is to determine which of the controllers is simpler to parameterize, as well as which provides better results in terms of response, stability and control accuracy. This formulates a problem that includes a comparison of the simplicity of implementation and performance quality, as well as considering the possibility of their application in a wider range of industrial processes, including HVAC systems and fluid control. The main task is to adjust the PID controller using the Ziegler–Nichols method in closed loop, and then implement the Fuzzy controller using Sugeno method for a comparative analysis of their performance under the same operating conditions.
The simulation system includes a circulation pump, a tank and several consumers connected via valves. Four simulation scenarios are defined:

1) Empty tank, set volume 20 L, consumer flow 60 L/min.
2) Empty tank, set volume 150 L, consumer flow 60 L/min.
3) Empty tank, set volume 500 L, consumer flow 60 L/min.

4) 500 L tank, three consumers with flow Q1 = 60 L/min, Q2 = 40 L/min, Q3 = 20 L/min, at a duty cycle of 60 s.

Both controllers are exposed to identical demands, while a graphical analysis of their responses provides a basis for assessing which control method enables faster adaptation, greater accuracy and steadier performance.

PID CONTROLLER TUNING

PID controller is defined with next relation, [5]:

$$u = K_p e + K_i \int_0^t e(\tau)d\tau + K_d \frac{de}{dt} \quad (1)$$

Setup of the PID controller was made to have a water volume in the tank as a measured process variable and desired water volume in the tank as a setpoint. PID control module was developed using the formula (1). Following step was applying the Ziegler-Nichols closed loop method. First step of the method was to set all PID parameters to zero. Next step was to increase the ultimate gain (K_u) until the oscillations were with constant amplitude. When the constant amplitude is reached, ultimate period (T_u) is measured. Measured K_u is 140 and T_u is 10 seconds. Final tuning step is applying formulas from the Table 1, [6].

Table 1. *Ziegler-Nichols settings for the continuous cycling method*

Controller type	K_p	T_i	T_d
P	0.5 K_u	-	-
PI	0.45 K_u	T_u /1.2	-
PID	0.6 K_u	0.5 T_u	0.125 T_u

FUZZY LOGIC CONTROLLER TUNING

The first step in preparing the Fuzzy logic controller is to define the fuzzy sets and membership functions, [7], [8], [9]. Two input variables are made so the system as similar as possible to the system we control with a PID controller.
Input variables are:

- Water volume in the tank, represented as a percentage of the setpoint (low, optimal and high)
- Pump flow represented as a percentage depending on the declared pump flow (low, medium and high)

Membership functions of the water volume in the tank are defined as:

$$\mu l = \begin{cases} 0, x > -25 \\ \dfrac{-25 - x}{-75}, -50 \le x \le -25 \\ 1, x < -50 \end{cases} \quad \mu o = \begin{cases} 0, x < -50 \\ \dfrac{x}{-50}, -50 \le x \le 0 \\ \dfrac{50 - x}{50}, 0 < x \le 50 \\ 0, x > 50 \end{cases} \quad \mu v = \begin{cases} 0, x < 25 \\ \dfrac{100 - x}{75}, 25 \le x \le 100 \\ 1, x > 100 \end{cases}$$

Membership functions of the pump flow are defined as:

$$\mu l = \begin{cases} 0, x > 25 \\ \dfrac{25 - x}{25}, 0 \le x \le 25 \\ 1, x \le 0 \end{cases} \qquad \mu m = e^{-\frac{(x-50)^2}{2x12.5^2}} \qquad \mu h = \begin{cases} 0, x < 75 \\ \dfrac{100 - x}{25}, 75 \le x \le 100 \\ 1, x > 100 \end{cases}$$

The Fuzzy rules applied to this controller are:

1) IF water volume IS low AND pump flow IS low THEN Pump Command = 100%.
   This rule reacts to a critically low water volume by increasing the pump's operation to quickly raise the water volume.
2) IF water volume IS low AND pump flow IS high THEN Pump Command = 50%.
   Although the water volume is low, the high pump flow means that the pump is already operating, so we reduce the intensity to avoid filling too quickly.
3) IF Water volume IS high THEN Pump Command = 5%.
   We reduce the pump's operation to avoid overflow.
4) IF water volume IS optimal THEN Pump Command = 40%.
   We maintain moderate pump operation to maintain a stable water volume.
5) IF water volume IS high AND pump flow IS low THEN Pump Command = 1%.
   If the water volume is already high and the pump flow is low, it is best to stop the pump to avoid unnecessary energy consumption and the risk of overflow.
6) IF the error relative to the setpoint IS negative AND IF water volume of the optimal < 95%, THEN the Pump Command = 60%
7) IF the error relative to the setpoint IS positive AND IF water volume of the optimal < 95%, THEN the Pump Command = 10%
   Since the system is generally designed to operate the pump at approximately 50% of power, by using rules 6 and 7, the system will approach the setpoint in a better way.
8) IF water volume IS low AND pump flow IS optimal THEN Pump Command = 90%
   We introduce this rule to regulate operation while the water volume is very low and to speed up the filling.

RESULTS AND DISCUSSION

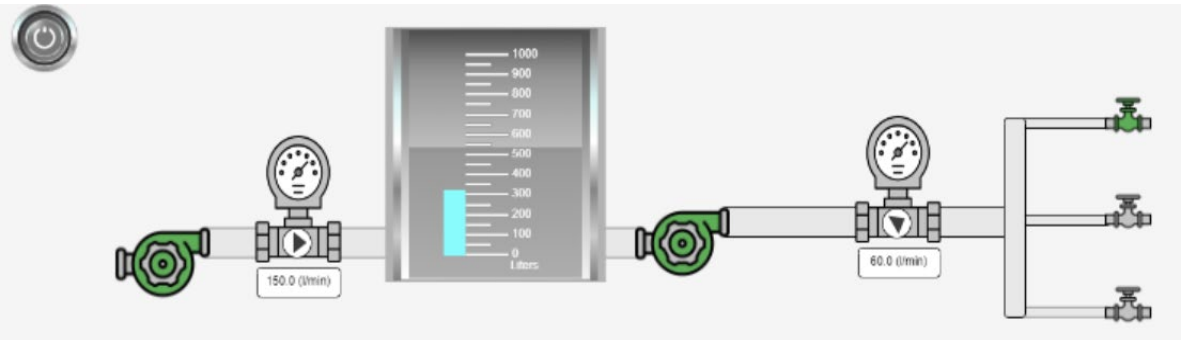


Fig. 1. *Visual representation of the system*

On the visual representation of the system (simulation) (Fig. 1), there is a system for controlling the water volume and stable supply to consumers. On the left side of the picture there is a pump that refills and controls the water volume in the tank. During active operation, without an alarm, it is colored green, thus giving a signal about its operation. Next to it is a flow meter, where the current flow during system operation is monitored. In the central part of the picture there is a tank that, in addition to the basic function of storing water, has the function of ensuring

a stable flow, relieving the feed pump and also, with additional settings, can be set to operate at more favorable hours and make the system more energy efficient. On the right side of the picture there is a pump that supplies consumers with water. Next to it is a flow meter on which you can monitor the flow of the currently active valve and the entire consumer side in the case of parallel operation. In the right corner there are three valves, representing three consumers. Each of the valves has adjustable flow and operating time, and the plan is, as in real conditions, for them to operate sequentially.

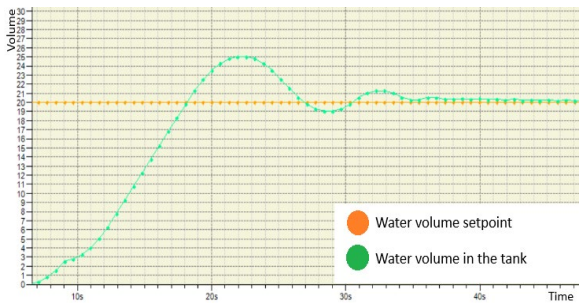


Fig. 2. *Simulation scenario 1 PID*

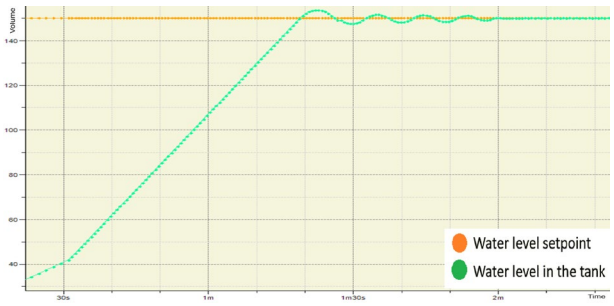


Fig. 3. *Simulation scenario 2 PID*

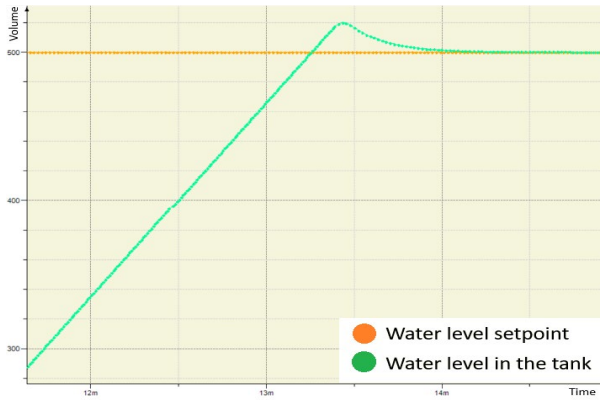


Fig. 4. *Simulation scenario 3 PID*

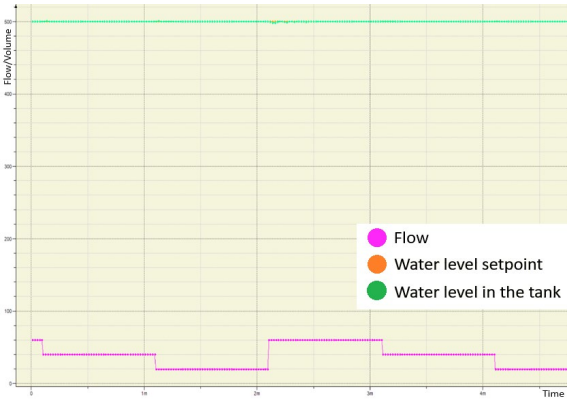


Fig. 5. *Simulation scenario 4 PID*

On the simulations 1 and 2, it can be seen that the system had a larger error at a higher setpoint. In both cases, it was necessary to oscillate around the setpoint before the value stabilized. In simulation 3, the system responded better than in the first two simulations. The first jump over the setpoint was less than 5% and the system approached the setpoint moderately without additional oscillations. On the simulation 4, the purple color represents the consumer, i.e. water consumption by the valve. At the section 2m and 10 seconds it can be noticed a jump from 20 to 60 l/min, at the section 3m and 10 seconds the flow changes from 60 to 40 l/min and at 4m and 10 seconds the flow drops from 40 to 20 l/min.

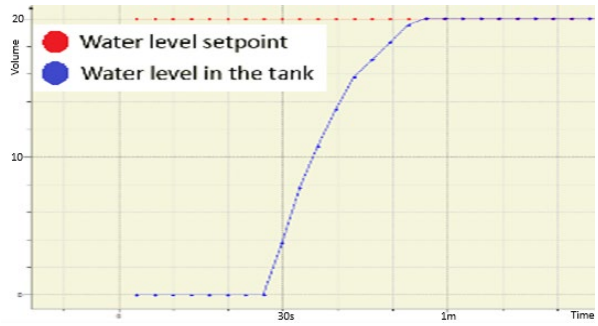


Fig. 6. *Simulation scenario 1 Fuzzy*

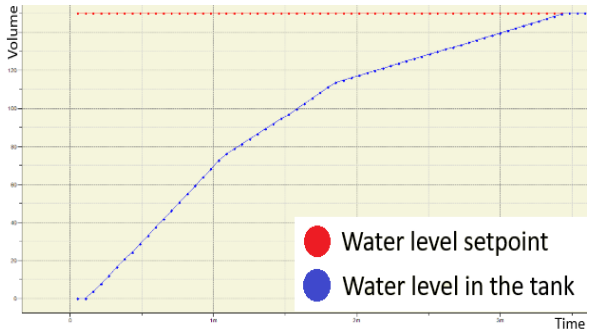


Fig. 7. *Simulation scenario 2 Fuzzy*

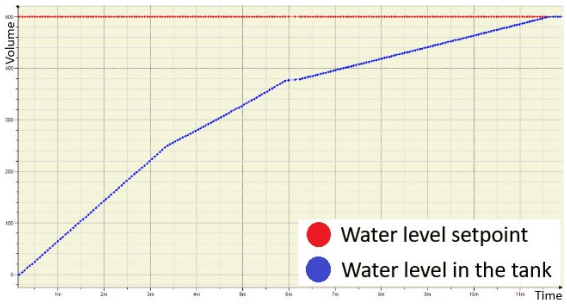


Fig. 8. *Simulation scenario 3 Fuzzy*

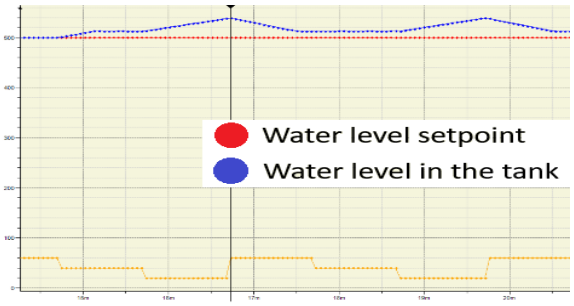


Fig. 9. *Simulation scenario 4 Fuzzy*

On the simulations 1, 2 and 3, the Fuzzy controller shows a stable response without overshooting the setpoint, and when reaching the setpoint it remains stable. On simulation 4, it can be seen that the Fuzzy controller does not respond well to flow changes, which can be further resolved by adjusting the rules and changing the values

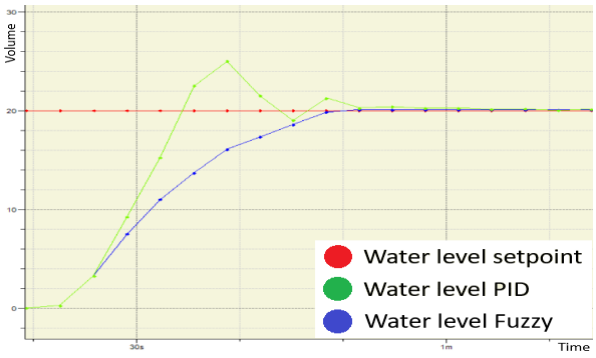


Fig. 10. *Simulation scenario 1 Fuzzy & PID*

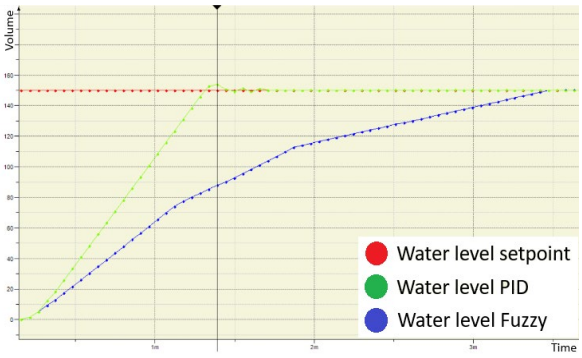


Fig. 11. *Simulation scenario 2 Fuzzy & PID*

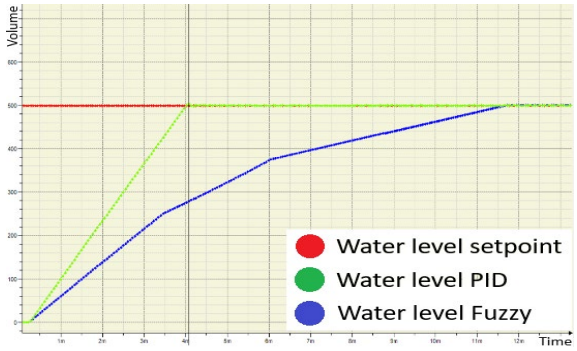


Fig. 12. *Simulation scenario 3 Fuzzy & PID*

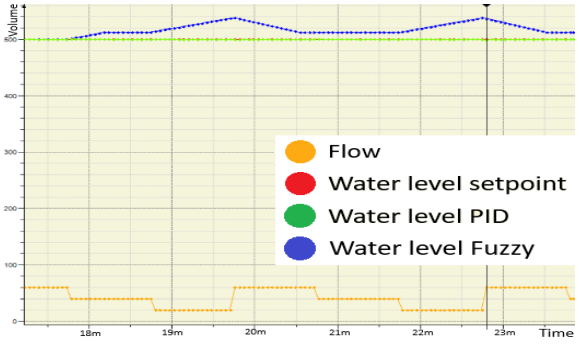


Fig. 13. *Simulation scenario 4 Fuzzy & PID*

By comparing the PID controller and Fuzzy controller, it is noticeable that the PID controller is much more reactive, but there are also certain oscillations until stabile state is reached. With the Fuzzy controller, reaching the setpoint is much more uniform and without overshoots. In the Fig13, it can be seen that the PID controller responds well to changes in flow, while Fuzzy controller has difficulties reaching the stable state.

CONCLUSION

By analyzing the PID controller tuned by the Ziegler–Nichols method and the Sugeno Fuzzy controller, the advantages and limitations of both approaches are clearly observed. The PID controller, based on precise mathematical operations, allows for rapid achievement of stable system operation, with minimal oscillations and controlled jumps of the set value. On the other hand, the Fuzzy controller provides greater expressiveness in defining the desired system

behavior and allows for fine adaptation in accordance with the complexity of real processes. Although its reaction is less pronounced for certain flow changes, by carefully adjusting the rules and membership functions, it is possible to achieve a response that surpasses the traditional PID in terms of stability and flexibility. The aim of the work was to balance the time and effort in tuning both controllers, in order to obtain a realistic insight into the performance when putting the system into operation. From the aspect of programming implementation, the PID controller is simpler to code and apply, while the Fuzzy controller, thanks to its flexibility, allows for more precise control and a higher quality of the final result. This comparative analysis emphasizes that the choice of controller should depend on the specific requirements of the system, where the balance between response speed and stability is a key criterion.

REFERENCES

[1] ABB, Automation Builder platform software, downloaded from: https://new.abb.com/plc/automationbuilder/platform/software, accessed 2025.
[2] ABB, PM5052-T-ETH, downloaded from: https://new.abb.com/products/1SAP124000R0072/pm5052-t-eth, accessed 2025.
[3] Hang, C.C., Åström, K.J. and Ho, W.K., Refinements of the Ziegler-Nichols tuning formula, IEE Proceedings D (Control Theory and Applications), Vol.132(2), pp. 111-118, 1991.
[4] Hambali, N., Masngut, A., Ishak, A.A., Janin, Z., Process Controllability for Flow Control System Using Ziegler-Nichols (ZN), Cohen-Coon (CC) and Chien-Hrones-Reswick (CHR) Tuning Methods, IEEE International Conference on Smart Instrumentation Measurement and Applications (ICSIMA), pp.1-5, 2014.
[5] Åström, K. J., & Murray, R. M. (2010). *Feedback systems: An introduction for scientists and engineers*. Princeton University Press, pp. 293-298, 2008.
[6] H. Efheij and A. Albagul, "Comparison of PID and Artificial Neural Network Controller in on line of Real Time Industrial Temperature Process Control System," in Proc. IEEE 1st Int. Maghreb Meeting Conf. Sci. Tech. Automat. Control Comput. Eng. (MI-STA), Tripoli, Libya, pp. 111–115, May 2021.
[7] Zadeh, L.A., Fuzzy Sets, Information and Control, Vol. 8, No. 3, pp. 338-353, 1965.
[8] Iancu, I., A Mamdani, Type Fuzzy Logic Controller, Fuzzy Logic: Controls, Concepts, Theories and Applications, InTech, pp. 55-64, 2012.
[9] T. Yulianto, S. Komariyah, and N. Ulfaniyah, "Application of fuzzy inference system by Sugeno method on estimating of salt production," AIP Conference Proceedings, vol. 1867, August 2017.

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ENERGY STATES OF ELECTRONS IN LAYERED GRAPHENE

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Abstract: In this paper, the quantum Green's function method was used to find the electron energy spectra and determine their density of states for single and bilayer graphene. On this basis, the electronic contribution to the thermodynamic properties of these layered graphenes is analysed below and compared with experimental data.
Key words: Graphene, electrons, quantum Green's functions, energy spectra, specific heat.

INTRODUCTION

Carbon - one of the most common chemical elements in nature - is characterised by a large number of its allotropic modifications, which result from the ability of carbon atoms to form various *sp*-hybridized bonds: tetrahedral (sp^3 - diamond), trigonal (sp^2 - graphite, fullerene), and/or linear (*sp* - carbyne). The most common form of carbon - graphite - is a layered structure in which the interaction between the layers occurs through weak van der Waals bonds, in which the binding energy between the atoms in the layer is more than ten times greater than the interaction energy between the layers, which essentially determines the basic (physical and chemical) properties of graphite, but also the possibilities for separation into individual layers, each of which is graphene. Graphene can therefore be considered as a monolayer of graphite in which the carbon atoms are assembled into an ideal hexagonal crystal structure, as shown in Figure 1 (defined in [1]).
This structure consists of two equivalent triangular sublattices - in one atom of "type" A and in the other atom of "type" B, the atom type being a conditional feature, since both A and B is carbon atoms that do not differ from each other. Different symbols for them are only introduced to indicate the affiliation to "their" sublattice. The carbon atoms B form two triangular sublattices that interpenetrate each other.

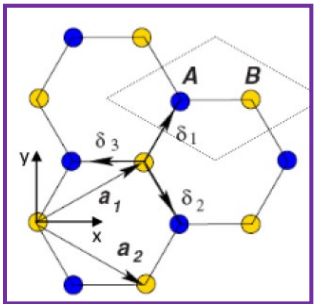


Fig. 1. *Graphene crystal structure*

Figure 1 shows two elementary translation vectors $\vec{a}_1$ and $\vec{a}_2$ and a primitive cell constructed on these vectors (rhomb - dashed line). Also shown in this figure are the vectors $\vec{\delta}_{1,2,3}$ connecting a particular carbon atom from one sublattice to its three nearest neighbours from another sublattice. Each of the two vectors transforms sublattice B into sublattice A.

The elementary translation vectors from Fig. 1 are given as:

$$\vec{a}_1 = a\left(\frac{3}{2}, \frac{\sqrt{3}}{2}\right); \quad \vec{a}_2 = a\left(\frac{3}{2}, -\frac{\sqrt{3}}{2}\right), \tag{1}$$

where the parameter $a = 0{,}142\ \mathrm{nm}$ - represents the side of the hexagon, i.e.,the distance between the nearest neighbors. The vectors from (1) have a length $a\sqrt{3}$ over which a primitive cell can be constructed – a rhombus connecting four "yellow" atoms. Within the rhombus, there must be a "blue" atom, so that the primitive cell contains two atoms.

The coordinates of the vector $\vec{\delta}_i,\ i = 1{,}2$, calculated from the selected atom of the sublattice B are then:

$$\vec{\delta}_1 = a\left(\frac{1}{2}, \frac{\sqrt{3}}{2}\right); \quad \vec{\delta}_2 = a\left(\frac{1}{2}, -\frac{\sqrt{3}}{2}\right); \quad \vec{\delta}_3 = a(1{,}0), \tag{2}$$

and the reciprocal lattice vectors are equal to:

$$\vec{b}_1 = \frac{2\pi}{3a}(1, \sqrt{3}); \quad \vec{b}_2 = \frac{2\pi}{3a}(1, -\sqrt{3}). \tag{3}$$

These vectors and the vectors $\vec{a}_{1,2}$ form a primitive cell in the form of a rhombus, and the Brillouin zone can be chosen in the form of a regular hexagon, as in Fig. 2 (defined in [1]).

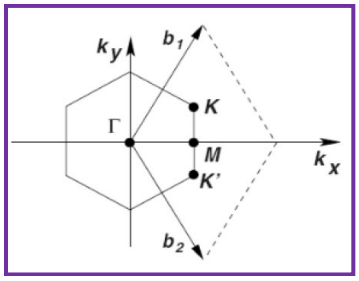


Fig. 2. *Primitive reciprocal lattice cell and Brillouin zone: point Γ is the centre of the zone, points K and K´ are Dirac points at the corners of the Brillouin zone, and point M lies in the centre of the side of the hexagon*

The points K and K´ lie alternately in the vertices of the Brillouin zone. All three points K are connected by reciprocal lattice vectors and are therefore equivalent (analogue all three points K´). No point K can be connected to any point K´ by the reciprocal lattice vector and they are therefore equivalent. Their coordinates are therefore:

$$\mathrm{K}: \frac{2\pi}{3\sqrt{3}a}(\sqrt{3}, 1); \quad \mathrm{K}': \frac{2\pi}{3\sqrt{3}a}(\sqrt{3}, -1). \tag{4}$$

The positions of these points and their surroundings essentially determine the electrical properties of graphene.

It is known [1,2–5] that three of the four valence electrons of each carbon atom in graphene are responsible for the formation of the lattice; each atom binds strongly to its three nearest neighbors via these three electrons in sp_2 hybridized states and forms chemical bonds. This means that the electronic wave functions are a linear combination of the atomic state functions 2*s*, $2p_x$, and $2p_y$. *Sp2-hybridised* electrons form a completely filled deep valence band. The fourth valence electron is therefore practically free. It is in the $2p_z$ state (the *z*-axis is perpendicular to the plane of the graphene) and can participate in elementary charge transport processes and optical transitions.

ELECTRON STATES IN MONOLAYERED GRAPHENE

The Hamiltonian of the graphene monolayer in the nearest neighbor approximation can be written in the form [6]:

$$H = \sum_{i,j} E_0 \left(a_i^+ a_i + b_{i+\delta_j}^+ b_{i+\delta_j}\right) + \sum_{i,j} T \left(a_i^+ b_{i+\delta_j} + b_{i+\delta_j}^+ a_i\right), \tag{5}$$

where E_0 - the energy corresponding to the $2p_z$ orbital of the carbon atom of graphene, a_i^+ and a_i are the operators for the creation and annihilation of the electron of the carbon atom belonging to the i-th atom of sublattice A, b_i^+ and b_i - the operators of the creation and annihilation of the electron of the carbon atom belonging to the i-th atom of sublattice B, T is the jump energy between the nearest neighboring atoms (between the sublattices A and B), δ_j is the distance between the nearest neighboring atoms. The space of the reciprocal lattice is moved by Fourier transformations [7] of the form:

$$\begin{aligned} a_i &= \frac{1}{\sqrt{N}}\sum_{\vec{k}} a_{\vec{k}} \mathrm{e}^{-i\vec{k}\cdot\vec{r}_i}; b_i = \frac{1}{\sqrt{N}}\sum_{\vec{k}} b_{\vec{k}} \mathrm{e}^{-i\vec{k}\cdot\vec{r}_i}; \\ a_i^+ &= \frac{1}{\sqrt{N}}\sum_{\vec{k}} a_{\vec{k}}^+ \mathrm{e}^{i\vec{k}\cdot\vec{r}_i}; b_i^+ = \frac{1}{\sqrt{N}}\sum_{\vec{k}} b_{\vec{k}}^+ \mathrm{e}^{i\vec{k}\cdot\vec{r}_i}. \end{aligned} \tag{6}$$

After the transformations, the Hamiltonian (5) turns into:

$$H = \sum_{\vec{k}} E_0\left(a_{\vec{k}}^+ a_{\vec{k}} + b_{\vec{k}}^+ b_{\vec{k}}\right) + \sum_{\vec{k}}\left[f\left(\vec{k}\right) a_{\vec{k}}^+ b_{\vec{k}} + f^*\left(\vec{k}\right) b_{\vec{k}}^+ a_{\vec{k}}\right], \tag{7}$$

where

$$f\left(\vec{k}\right) = \sum_i T\mathrm{e}^{i\vec{k}\cdot\delta_j} \rightarrow f^*\left(\vec{k}\right) = \sum_i T\mathrm{e}^{-i\vec{k}\cdot\delta_j}, \tag{8}$$

Is the Fourier transform of the „jump" energy.

To find the electron dispersion law in the graphene monolayer, quantum Green's functions of the form are sought:

$$\begin{aligned} G_{\mathrm{A}} &= \langle\langle a_{\vec{k}} \left| a_{\vec{k}}^+ \right\rangle\rangle; G_{\mathrm{B}} = \langle\langle b_{\vec{k}} \left| b_{\vec{k}}^+ \right\rangle\rangle; \\ G_{\mathrm{AB}} &= \langle\langle a_{\vec{k}} \left| b_{\vec{k}}^+ \right\rangle\rangle; G_{\mathrm{BA}} = \langle\langle b_{\vec{k}} \left| a_{\vec{k}}^+ \right\rangle\rangle. \end{aligned} \tag{9}$$

The notations $\langle\langle \cdots | \cdots \rangle\rangle$, which were first introduced by Bogolyubov and Tyablikov [8], represent the averaging of operators over the corresponding canonical ensemble. To find the Fourier figure of the corresponding Green's function, Heisenberg's equations of motionare used for the given Green's functions:

$$\varepsilon\langle\langle A|B\rangle\rangle = \langle[A,B]_\eta\rangle + \langle\langle[A,H]_\eta|B\rangle\rangle. \tag{10}$$

Here the designation η indicates whether we are dealing with commutators or anticommu–tators. Since we are talking about electrons (fermions), we are dealing with anticommutators. The labeling $\langle\cdots\rangle$ represents the mean value [9].

Using the commutation relations [7,10,11], the expression for Green's function results from the equations of motion:

$$G_{\mathrm{A}} = \left(\varepsilon - E_0 - \frac{\left|f(\vec{k})\right|^2}{\varepsilon - E_0}\right), \tag{11}$$

and from the theory of quantum Green's functions [7–12] it is known that the pole of the Fourier figure of the Green's function $\mathrm{Re}\, G^{-1} = 0, \varepsilon \equiv \varepsilon + i0$, determines the dispersion law or the energy spectrum of the corresponding particle for which the equation of motion is written, and from (11) follows:

$$\varepsilon_{\vec{k}} = E_0 \pm \left|f\left(\vec{k}\right)\right|. \tag{12}$$

In the vicinity of Dirac points with the coordinates $K = \left(\frac{2\pi}{3a}, \frac{2\pi}{3\sqrt{3}a}\right)$ the following expression results for the Fourier transformation (8) from the energy spectrum (12):

$$f(k) = \hbar v_{\mathrm{F}} q; v_{\mathrm{F}} = \frac{3Ta}{2\hbar}; q = \sqrt{k_x^2 + k_y^2}. \tag{13}$$

where are:

$$v_{\mathrm{F}} = \frac{3Ta}{2\hbar};\ q = \sqrt{k_x^2 + k_y^2}, \tag{14}$$

hopping rate and two-dimensional wave vector.

Expression (12) agrees with the expression obtained by the method of strong bonding [13], and the magnitude of E_0 corresponds to the energy of the Dirac point. If we calculate the

electron energy as the difference to this, we can formally assume it to be $E_0 = 0$. The energy spectrum of the charge carriers then results as follows:

$$\varepsilon = \hbar v_{\mathrm{F}} q. \tag{15}$$

As can be seen, the spectrum of charge carriers in the case of a single-layer graphene is linear in the vicinity of the Dirac points. The surroundings of the points K and K´ are called valleys in accordance with semiconductor physics (Fig. 3, from [1]).

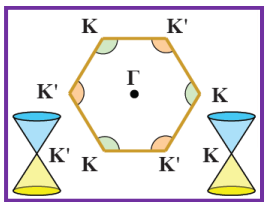


Fig. 3. *Energy spectrum in the vicinity of Dirac points*

The density of states of charge carriers in the graphene monolayer, based on the definition from the theory of Green's functions [7–12], is determined in this case as:

$$\begin{aligned} &g_{\pm}(\varepsilon) = \textstyle\sum_{k,\sigma} \delta(\varepsilon - \varepsilon_{\pm})\,; \varepsilon_{\pm} = \pm\hbar v_F q; \\ &g_{+}(\varepsilon) = 2 \cdot 2 \cdot \frac{A}{(2\pi)^2} \cdot 2\pi \int_0^{\infty} dqq\, \delta(\varepsilon - \hbar v_F q); \\ &g_{+}(\varepsilon) = \frac{2A}{\pi\hbar^2 v_F^2}\varepsilon; g_{-}(\varepsilon) = \frac{2A}{\pi\hbar^2 v_F^2}(-\varepsilon); \Rightarrow g(\varepsilon) = \frac{2A}{\pi\hbar^2 v_F^2}|\varepsilon|. \end{aligned} \tag{16}$$

Degeneracy is accounted for here by spin and by valleys.

ELECTRON STATES IN BILAYERED GRAPHENE

In bilayer graphene, there are transitions of charge carriers both between the atoms in the layer and between the layers. In the general case, there are various transitions between the layers, andthe most important one is$T_{\perp}$, i.e. the transition at an angle of 90º [14], which is marked in Fig. 4.

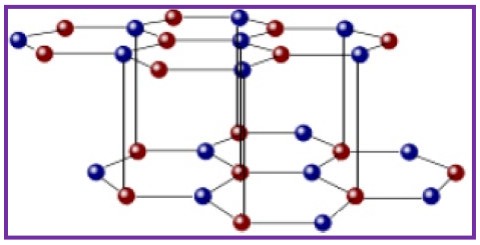


Fig. 4. *Crystal structure of bilayer graphene. The lines connecting the two graphene layers represent the interaction$T_{\perp}$ which is the most important of all coverage integrals (from [14])*

Hamiltonian for bilayer graphene is of the form [6]:

$$\begin{aligned} H = &\textstyle\sum_i E_0\left(a_i^{+(1)}a_i^{(1)} + b_i^{+(1)}b_i^{(1)}\right) + \sum_i E_0\left(a_i^{+(2)}a_i^{(2)} + b_i^{+(2)}b_i^{(2)}\right) + \\ &+ \textstyle\sum_{i,j} T\left(a_i^{+(1)}b_j^{(1)} + b_j^{+(1)}a_i^{(1)}\right) + \sum_{i,j} T\left(a_i^{+(2)}b_j^{(2)} + b_j^{+(2)}a_i^{(2)}\right) + \\ &+ \textstyle\sum_{i,j} T_{\perp}\left(a_i^{+(1)}b_j^{(2)} + b_j^{+(2)}a_i^{(1)}\right). \end{aligned} \tag{17}$$

Here $a_i^{+(1)}a_i^{(1)}$and$b_i^{+(1)}b_i^{(1)}$ are operators of creation and annihilation of electrons of sublattices A and B of the first layer, and $a_i^{+(2)}a_i^{(2)}$ and $b_i^{+(2)}b_i^{(2)}$ are operators of creation and annihilation of electrons of sublattices A and B of the second layer.

If we enter the space of the reciprocal lattice and use the corresponding Fourier transforms as in the expressions (6), we obtain:

$$H = \sum_{\vec{k}} \left[f(\vec{k}) \left(a_{\vec{k}}^{+(1)} b_{\vec{k}}^{(1)} + a_{\vec{k}}^{+(2)} b_{\vec{k}}^{(2)} \right) + \right.$$
$$\left. + f^*(\vec{k}) \left(b_{\vec{k}}^{+(1)} a_{\vec{k}}^{(1)} + b_{\vec{k}}^{+(2)} a_{\vec{k}}^{(2)} \right) \right] +$$
$$+ \sum_{\vec{k}} T_\perp \left(a_{\vec{k}}^{+(1)} b_{\vec{k}}^{(2)} + b_{\vec{k}}^{+(2)} a_{\vec{k}}^{(1)} \right). \quad (18)$$

In this expression it is already substituted that $E_0 = 0$.
If you now set up the equations of motion for the corresponding Green's functions, as in the case of single-layer graphene, and then solve the system of equations for the Green's functions, we find:

$$G_{\mathrm{AA}}^{(11)} = \left[\varepsilon - \frac{|f(\vec{k})|^2}{\varepsilon} - T_\perp^2 \left(\varepsilon - \frac{|f(\vec{k})|^2}{\varepsilon} \right)^{-1} \right]^{-1}, \quad (19)$$

for the electronic energy spectrum in the vicinity of the Dirac points, the dispersion law of two-layer graphene thus results in the following form:

$$\varepsilon = \pm \sqrt{v_{\mathrm{F}}^2 \hbar^2 k^2 + \frac{T_\perp^2}{2} \pm \sqrt{v_{\mathrm{F}}^2 \hbar^2 k^2 T_\perp^2 + \frac{T_\perp^4}{4}}}. \quad (20)$$

In contrast to a monolayer, bilayer graphene has an energy spectrum without a gap and a parabolic shape (as in Fig. 5 from [14]). Near the Dirac points, the energy spectrum of bilayer graphene can be described as follows:

$$\varepsilon \approx \pm \frac{\hbar^2 q^2}{2m^*}; m^* = \frac{|T_\perp|}{2v_{\mathrm{F}}^2} = 0{,}054\, m_{\mathrm{e}}, \quad (21)$$

where m^* is the effective mass of charge carriers, and m_{e} is the mass of electrons at rest.

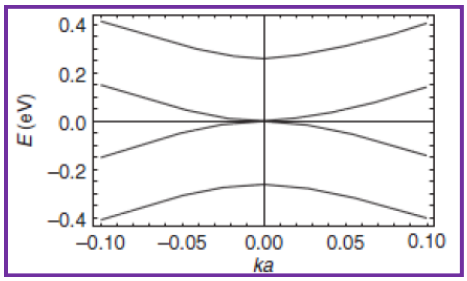


***Fig. 5**. Energy spectrum of electrons in bilayer graphene*

The density of charge carrier states, using the same procedure as in the graphene monolayer [15,16], was determined in the following form:

$$g(\varepsilon) = \sum_{\vec{k},\sigma} \delta\left(\varepsilon - \frac{\hbar^2 q^2}{2m^*} \right) = 2 \frac{A}{(2\pi)^2} \cdot 2\pi \int_0^\infty q dq\, \delta\left(\varepsilon - \frac{\hbar^2 q^2}{2m^*} \right);$$
$$\varepsilon < 0: \quad g(\varepsilon) = 0; \quad (22)$$
$$\varepsilon > 0: \quad \delta\left(\varepsilon - \frac{\hbar^2 q^2}{2m^*} \right) = \sum_{k_*} \frac{\delta(k-q)}{\left| \frac{d}{dq} \left(\varepsilon - \frac{\hbar^2 q^2}{2m^*} \right) \right|_{k=k_*}}; \quad \varepsilon = \frac{\hbar^2 q^2}{2m^*};$$

$$\delta\left(\varepsilon-\frac{\hbar^2q^2}{2m^*}\right)=\frac{\delta\left(k-\sqrt{2m^*\varepsilon/\hbar^2}\right)}{\frac{\hbar^2}{m}\sqrt{\frac{2m^*\varepsilon}{\hbar^2}}}+\frac{\delta\left(k+\sqrt{2m^*\varepsilon/\hbar^2}\right)}{\frac{\hbar^2}{m}\sqrt{\frac{2m^*\varepsilon}{\hbar^2}}}$$

$$g(\varepsilon)=\frac{A}{\pi}\cdot\sqrt{\frac{2m^*\varepsilon}{\hbar^2}}\frac{1}{\frac{\hbar^2}{m^*}\sqrt{\frac{2m^*\varepsilon}{\hbar^2}}}=\frac{A}{\pi}\frac{m^*}{\hbar^2}\theta(\varepsilon)$$

CONCLUSION

In this paper, the quantum Green's function method was used to determine the energy spectra of single and bilayer graphene. It is common to use the strong bond method (developed in [13]) in the late 1940s to determine the energy spectra of graphene. Quantum Green functions originates from quantum field theory and was used in condensed matter physics in the 1960s [18]. It should be noted that this field of science is expanding and is far from complete, as new areas of application are constantly being found. In this sense, this method is increasingly applied to new materials such as graphene and other low-dimensional systems. In this work, the energy spectra of single and bilayer graphene as well as the density of states for these structures were determined. All results are in agreement with the experimental data available to us [19–21].

REFERENCES

[1] Sokolik A.A.,Graphene and its Properties, RAN, Moscow, 2008. (In Russian)
[2] Jaćimovski S.K., Sajfert V.D., Šetrajčić J.P., Raković D.I., Electronic Contribution to Conductivity in Graphene, Quantum Matter **4**/6, 559-564, 2015.
[3] Jaćimovski S.K., Šetrajčić J.P., Vučenović S.M., Electron Heat Transport in Graphene, Proceedings 49th International October Conference on Mining and Metallurgy, 170-173, 2017.
[4] Jaćimovski S.K., Lamovec J., Vučenović S.M., Šetrajčić J.P., Thermal Conductivity of Graphene Monolayer in the Framework of Debye and Callaway Models, Proceedings 13th IC: Contemporary Materials (ISBN 978-99976-42-40-0), 71-78, 2021.
[5] Jaćimovski S.K., Lamovec J., Šetrajčić J.P., Quantum Properties of Graphene, International Symposium "100 Years of Quantum Mechanics: Science, Technology and Future", Program, p.5, Banja Luka, 2025. (In Serbian)
[6] Alisultanov Z.Z., The Thermodynamics of Electrons and the Thermoelectric Transport in Epitaxial Graphene on the Size-Quantized films, Physica E: Low-dimensional Systems and Nanostructures, PHYSE11827, 2015.
[7] Tošić B.S., Šetrajčić J.P., Jaćimovski S.K., Methods of Theoretical Physics, KPU, Zemun – Belgrade, 2018. (In Serbian)
[8] Bogolyubov N.N., Tyablikov V.S., Retarded and Advanced Green's Functions in Statistical Physics, DAN SSSR **123**/1, 53-56,1959. (In Russian)
[9] Tošić B.S., Statistical Physics, *Faculty of Sciences*, Novi Sad, 1978. (In Serbian)
[10] Davydov A.S., Theory of Solid State, Nauka, Moscow,1975. (In Russian)
[11] Rickayzen G., Green´s Functions and Condensed Matter, Academic Press, London, 1980.
[12] Mahan G.D., Many Particle Physics, Kluwer Academic/Plenum Publ., New York, 2000.
[13] Wallace P.R., The Band Theory of Graphite, Phys. Rev. **71**, 622, 1947.
[14] Katsnelson M.I., The Physics of Graphene, Cambridge University Press, London,2020.
[15] Mahan G.D., Condensed Matter in a Nutshell, Princeton University Press, New Jersey, 2011.

[16] Fuxiang Han, A Modern Course in the Quantum Theory of Solids, World Scientific Pub. Co. Inc., 2012.
[17] Falkovsky L.A., Thermodynamics of Electron-Hole Liquids in Graphene, arXiv1304.7885v1[cond-mat.mes-hall], 2013.
[18] Abrikosov A.A., Gorkov L.P., Dzyaloshinsky I.E., Methods of Quantum Field Theory in Statistical Physics, Fizmatgiz, Moscow, 1962. (In Russian)
[19] NovoselovK.S., et al., Room-Temperature Quantum Hall Effect in Graphene, arXiv:cond-mat/0702408v1 [cond-mat.mess-hall], 2007.
[20] Castro Neto A.H., et al., The Electronic Properties of Graphene, arXiv:0709.1163v2 [cond-mat.other], 2008.
[21] Eletskii A.V., Iskandaroval. M., Knizhnik A.A., Graphene: Fabrication Methods and Thermophysical Properties, Uspekhi Fizicheskikh Nauk **181**/3, 233 – 268, 2011.

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OVERVIEW OF RENEWABLE ENERGY SOURCES IN SERBIA AND IN THE WORLD

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Abstract: We are at the end of one epoch when fossil fuels, conventional or non-renewable energy sources can not be the basis for our future development planning. Consequently, since all of these resources are exhausted, it is necessary to look for and bring in some new sources of energy in usage, and it is the moment when a person turns to nature or to renewable energy sources. Renewable energy sources are inexhaustible energy sources that are obtained from nature and are renewed at a certain interval of time. This paper presents the comparison of some different types of renewable energy sources that are used in Serbia, opposed to those that are used in the world. The paper also presents some regions on the territory of Serbia which has a good potential for some different types of the RES.
Key words: Renewable energy sources (RES), potential, thermal, Serbia, world.

INTRODUCION

Renewable energy sources have significant potential for improving the development of humanity. Energy from renewable sources - water, wind, sun and biomass, among others - can facilitated access to clean and safe energy for millions of people. It can provide an incentive for social and economic development, helping to cope with environmental challenges, and has a key role in successfully dealing with climate change. First of all, we need to define what renewable energy sources are. Renewable energy sources are inexhaustible energy sources of nature that are renewed at a certain time interval, in whole or in part. These energy sources are used for the production of electrical, thermal and mechanical energy, and their significant sustainability is environmental harmony, with reduced or reducing CO_2 emissions in the process of energy production. The usage of this elements are now the most important thing for us because we exhausted some of existing sources of energy, [1,2].
Renewable energy sources can be divided into two categories, [3]:

- Traditional renewable energy sources like: biomass and energy of large hydropower plants and
- „ New renewable energy sources" such as energy of Sun, wind energy, geothermal energy, ect.

The development of renewable energy sources, especially from wind, water, sun and biomass, is important for several reasons, [3]:

- These energy sources play a very important role in reducing carbon dioxide (CO_2) emissions into the atmosphere. This is also an important part of the European Union's policy.
- Increasing the contribution of renewable energy sources we increase the energy sustainability of a country's system. At the same time it helps to improve the security of energy delivery and thus reduces the dependence on imports of energy raw materials as well as electricity,
- Renewable energy sources are expected to become economically competitive with conventional energy sources in due course.

Today, new energy sources produce only a small part of the world's total energy. This share in the future should increase considerably as non-renewable energy sources are getting smaller and their reserves are on the brink, and their detrimental impact is more and more pronounced in the last few years. The Sun, without whom there is no life on our planet, gives Earth several thousand times more energy than mankind is able to spend at the current stage of development. Everything is in favor of the fact that renewable sources can and must start to be better exploited and that if we do wisely, we do not have to worry about energy after fossil fuels.

OVERVIEW OF RENEWABLE ENERGY SOURCES IN SERBIA

Renewable energy sources are the main backbone of Serbia's energy independence in the future. The total potential of energy from renewable sources can satisfy a quarter of the annual needs of Serbia. The total technically available potential of renewable energy sources in the Republic of Serbia is estimated at 5.65 million ten for the year. Of this potential, 1.054 million ten of biomasss (mainly firewood) and 909 thousand ten of hydroelectric power plants. As we said before, biomass present a huge energetical potential for Serbia, [4,5].
The potential of biomass is estimated at 3.448 million ten and in the total potential of RES accounts for 61%. Of this potential, the greatest part is the potential of wood biomass - 1.53 million ten and the potential of agricultural biomass - 1.67 million ten (residues in farming, livestock breeding, fruit growing, viticulture and primary fruit processing), while the potential of biodegradable municipal waste is estimated at 205 thousands of ten. Biodegradable waste (excluding municipal waste) consists of waste edible oils and animal waste (waste slaughterhouse waste) in the total amount of 0.043 million ten / year. Wood biomass is mainly in the area of central Serbia, and agricultural biomass in the area of Vojvodina. However, while the degree of utilization of potential is wood (forest) biomass is relatively high (66.7%), the potential of agricultural biomass is slightly used (~ 2%), while the potential of biodegradable municipal waste is not used at all, [4,5].
The total theoretically available hydropower potential of the waters that flow on the territory of the Republic of Serbia is around 25000 GWh / year. The largest part of the hydro-potential (over 70%) is concentrated only on several watercourses with a potential above 1000 GWh / year: Danube, Drina, Velika Morava, Lim and Ibar. On the other hand, on several rivers in the Republic of Serbia, hydro power potential will only be able to be partially used, due to the priority of water management of water, because some rivers are planned as sources of regional water supply systems: Toplica, Crni Timok, Rasina, Studenica, Veliki Rzav, Mlava , Lepenac, etc. The technically usable potential in the Republic of Serbia is around 19.5 TWh / year, of which about 17.7 TWh / year at facilities greater than 10 MW. So far 16 hydropower plants have been built and produced on average about 10.5 TWh per year. The total technical potential of hydroelectric power plants up to 10 MW is estimated at around 1800 GWh per year.
Wind energy in the Republic of Serbia can be used in the area of the Kosavsko area, southern Banat, the area of eastern Serbia, the eastern side of Kopaonik, the area of Zlatibor and Pester and on the location of mountain-crossings that have elevation above 800 m. For the clearer understanding of the potential, it is necessary to continue to devote wind measurements (started in southern Banat and eastern Serbia) in order to produce wind atlas, as one of the conditions for investing in wind power generation capacities. The technically usable wind potential is determined on the basis of the existing technical possibilities of the electric power system to take this energy. Additional assumptions in determining the potential are that the maximum variation of wind power generation will not coincide with the maximum variations in the production of electricity from solar power plants and that the maximum variation will not exceed 90% of the total installed capacity. This means that in the installed capacities it is possible to have 500 MW with the current size of the tertiary power reserve, which can be provided in thermal power plants and accumulation hydroelectric power plants. Considering the maximum possible production of wind farms with this installed power, they

can count on their maximum technically usable potential of 1200 GWh / year (0.103 Mtoe / year), [4,5].

Energy of the Sun represents the energetic potential of the Republic of Serbia, which can be used for the production of heat or electrical energy. The huge part of the territory of the Republic of Serbia, the number of hours of solar radiation is significantly higher than in many European countries (between 1500 and 2200 hours per year). The average intensity of solar radiation in the territory of the Republic of Serbia ranges from 1.1 kWh / m^2 / day in the north to 1.7 kWh / m^2 / day in the south - during January, and from 5.9 to 6.6 kWh / m^2 / day - during July. Annually, the average value of the energy of radiation is 1200 kWh / m^2 / year in northwestern Serbia, up to 1550 kWh / m^2 / year in southeastern Serbia, while in the central part it is about 1400 kWh / m^2 / year. The technically usable energy potential for the conversion of solar energy into heat energy (for the preparation of hot water and other purposes) is estimated at 0.194 million ten yearly, assuming the use of solar thermal collectors in 50% of available facilities in the country, [4,5].

The Republic of Serbia is located in the zone of favorable geothermal potentials and resources. Geothermal energy implies petrothermal and hydrogeothermal energy resources that the Republic of Serbia has abundantly used. The use of geothermal energy for heating and other energy purposes in the Republic of Serbia is at an early stage and very modest in terms of potential and resources. The geothermal potential of the Republic of Serbia clearly shows the existence of a large number of spas and natural springs with water temperatures greater than 30°C, and a different degree of natural diversity. Based on the existing measurements, the heat flux is above the average for Europe (60 mW / m^2), or ranges from 80 to 120 mW / m^2. Natural and artificial sources of thermal water have been identified in the territory of more than 60 municipalities. The water temperature is usually in the range of 40°C, and only in the territory of six cities / municipalities (Vranje, Sabac, Kuršumlija, Raska, Medveđa, Apatin) the water temperature is over 60°C. Average water flows from existing sources and wells are on average up to 20 l / s. At several locations, the flow of water exceeds 50 l / s (Bogatic, Kuršumlija, Pribojska Banja, Niška Banja), and only at one location the flow of water exceeds 100 l / s (Banja Koviljača). The total thermal power that could be obtained by utilizing all existing thermal water sources is about 216 MW_t, with the production of thermal energy of 180 thousand ten. Significant but unimaginable geothermal potential lies in the use of negative and sedimented oil and gas wells in Vojvodina, where the exploitation is completed, [4,5].

These are all the most recent facts related to the RES in Serbia, but to see that Serbia had progression on this way, on Figure 1. we would show the facts related to the RES from 2012.

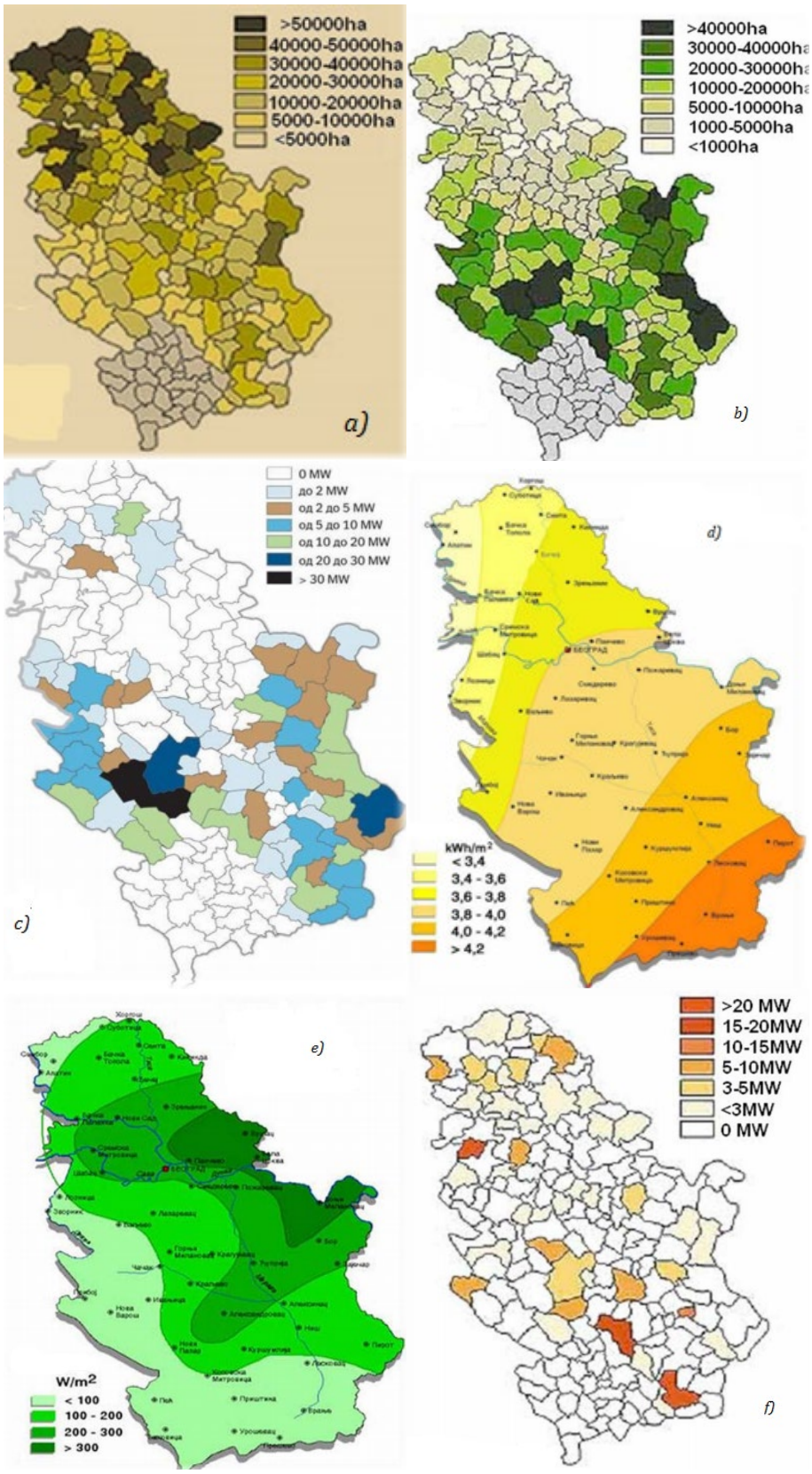


Fig. 1. *Potential for some parts of Serbia for using the RES and the numbered datas from 2012. a)sources of biomass – arable lands, b) sources of biomass – surface with the forests, c) hidroenergy - total power of small hydropower plans, d) areas with a large number of sunny hour – annual average of the daily energy of global radiation on the horizontal surface, e) wind energy – average annual wind power at 100 m, f) geothermal energy – total power from geothermal sources, [1].*

OVERVIEW OF RENEWABLE ENERGY SOURCES IN THE WORLD

Renewable technologies include hydropower, solar, wind, geothermal and modern biofuel production (including modern forms of waste-to-biomass conversion). The change & mix of modern renewable consumption over the last 50 years is shown in the Figure 2. below. This is measured in terawatt-hours per year and can be viewed across a range of countries and regions. Globally, the world produced approximately 5.9 TWh of modern renewable energy in 2016. This represents a 5 to 6-fold increase since the 1960. Here we see that hydropower remains the dominant form of modern renewables consumption, accounting for almost 70 percent. Despite absolute growth in production, hydropower's share is, however, declining as other renewable technologies grow, [6,7].

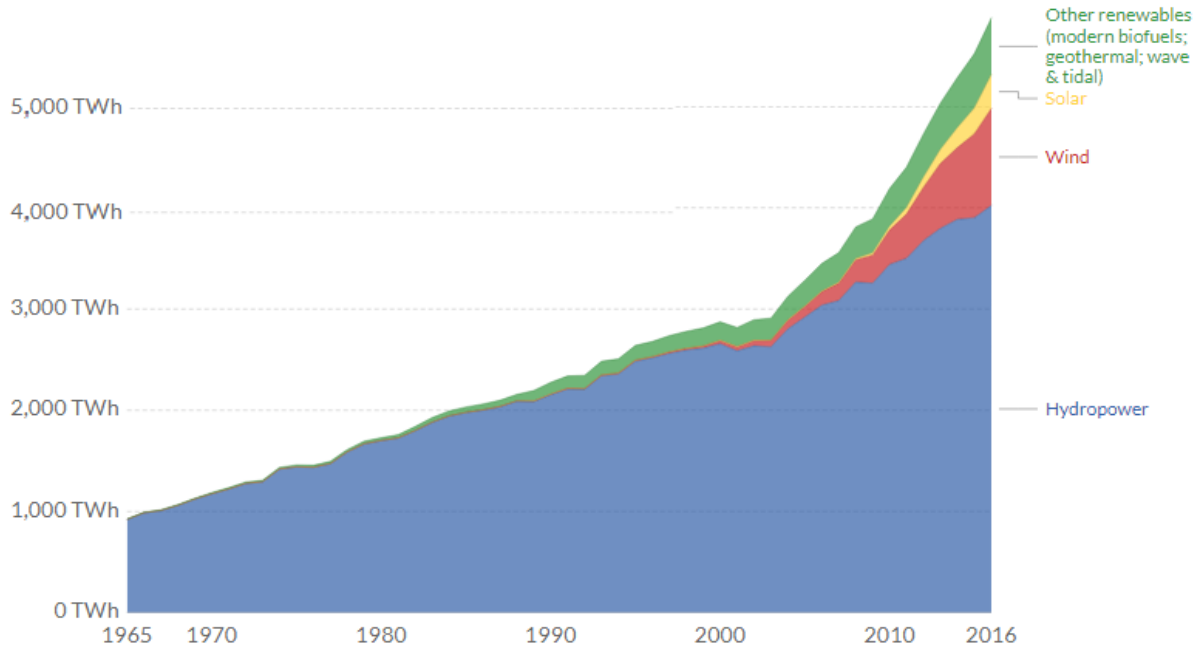


Fig. 2. *Modern renewable energy consumption over the last 50 years in the world, [6].*

Renewable energy sources represent the future of every country that wants to sustain development and represents the general field that needs to be invested in the great powers. It is important to note what are the leading world countries that are at the top of the use of renewable energy sources. These countries are shown in Figure 3.

	1	2	3	4	5
Investment in renewable power and fuels (not including hydro over 50 MW)	**China**	United States	Japan	India	Germany
Investment in renewable power and fuels per unit GDP[1]	**Marshall Islands**	Rwanda	Solomon Islands	Guinea-Bissau	Serbia
Geothermal power capacity	**Indonesia**	Turkey	Chile	Iceland	Honduras
Hydropower capacity	**China**	Brazil	India	Angola	Turkey
Solar PV capacity	**China**	United States	India	Japan	Turkey
Concentrating solar thermal power (CSP) capacity[2]	**South Africa**	-	-	-	-
Wind power capacity	**China**	United States	Germany	United Kingdom	India
Solar water heating capacity	**China**	Turkey	India	Brazil	United States
Biodiesel production	**United States**	Brazil	Germany	Argentina	Indonesia
Ethanol production	**United States**	Brazil	China	Canada	Thailand

Fig. 3. *Top five countries for annual investments, net capacity and for production based on using the RES in 2017, [8].*

CONCLUSION

As we said renewable energy sources have significant potential for improving the development of humanity. Energy from renewable sources - water, wind, sun and biomass, among others - can facilitated access to clean and safe energy for millions of people. It can provide an incentive for social and economic development, helping to cope with environmental challenges, and has a key role in successfully dealing with climate change.
The use of RES in the world has seen a significant increase in all sectors and global investments in RES set new record. And this trend is striving to grow even more. Serbia has significant energy potential in this area, but resources are underused in relation to the rest of the world.
Energy from renewable sources, such as the sun and wind, is approximately equally distributed in the countries of the world, and no one owns that energy.

REFERENCES

[1] Despotović, Ž., Renewable energy sources – situations and perspectives in Serbia and in the world,presentations, Belgrade, 2012.
[2] Buchla, D., Kissell, T., Floyd, T., Renewable energy systems, Pearson, 2014.
[3] https://www.industrija.rs/vesti/clanak/oie-energija-buducnosti
[4] http://www.rsjp.gov.rs/strategija_razvoja_energetike_do_2025.pdf
[5] Brnabić, A., Turković, M., Roadmap for the development of renewable energy sources in Serbia and the environment: consideration of energy policy in the field of renewable energy sources, Center for International Cooperation and Sustainable Development (CIRSD)., Alta Nova,Belgrade, 2015.
[6] https://ourworldindata.org/renewable-energy#references
[7] Renewable Energy, International Energy Agency, 2002.
[8] http://www.ren21.net/wpcontent/uploads/2018/06/178652_GSR2018_FullReport_web.pdf

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ANALYSIS AND OPTIMIZATION OF THE WATER SUPPLY SYSTEM "BELO BLATO"

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Abstract: This paper deals with the analysis and optimization of the water supply system in the settlement of Belo Blato, with the aim of improving reliability and efficiency in water distribution. A hydraulic calculation was used to evaluate the average and maximum flow rates, pressure losses in pipelines, total head, and required pump power under different operating scenarios. Special emphasis was placed on the summer season, when water consumption increases by about 30%, as well as on the impact of adding a third well to the system's performance. The results show that the existing system does not meet demand during periods of increased consumption, while the installation of an additional well and the enhancement of pump capacity enable stable and reliable water supply. Based on the obtained results, guidelines were defined for improving system performance, which can contribute to reducing pressure losses and increasing the quality of service to consumers.
Key words: Water Supply, Hydraulic Calculation, Pressure Losses, Flow Rate, Pumps.

INTRODUCTION

Water supply systems represent vital infrastructure for any settlement, enabling the provision of clean and safe drinking water to the population for domestic, sanitary, and other daily needs. At the beginning of the twentieth century, the purpose of water distribution networks (WDNs) was to support economic and industrial development and to provide fire protection. The objective of modeling studies was to establish criteria for the hydraulic verification of WDN projects in relation to the water demand of different categories of users. Supplying consumers with uncontaminated drinking water is of essential importance for human life, and the water distribution system represents a key infrastructure for meeting this need [1,2].
Urban water distribution systems are facing increasing challenges due to energy inefficiencies caused by hydraulic anomalies, such as pipe aging, breakages, consumption variability, and the suboptimal operation of pumps and valves [3]. Effective planning, analysis, and optimization of these systems are crucial for ensuring stable and reliable water supply, particularly under conditions of variable demand and seasonal load. Water pumps are devices designed for transporting liquids, primarily water, and are most commonly used in smaller capacities, as they are more efficient for increasing flow velocity. Management of the water distribution system is an integral part of the water supply industry. It is necessary to ensure that systems operate efficiently while maintaining high service quality at the lowest possible cost [4,5].
Energy costs for pump operation represent the dominant share of the operational expenses of a water supply system [6]. Pump operation is constrained by pressure levels relative to the actual electrical power required to drive them, while pump efficiency is reflected in head and flow rate. The efficiency of water network optimization, when observed in terms of computational effort, depends on the speed of the hydraulic calculation; nevertheless, it is also necessary to account for factors such as pump type, head, flow variability, and the transition from laminar to turbulent flow caused by laminar instability. Flow transitions can be influenced by various factors, including wall roughness, head, pressure, and temperature [7-10]. The settlement of Belo Blato faces challenges in optimizing its water supply system to meet the population's needs, especially during the summer season when water consumption significantly increases. This paper addresses the analysis and optimization of the Belo Blato water supply system, focusing on hydraulic calculation, evaluation of pressure losses, total head, and required pump power. The steps for calculating nominal flow rates will be

presented, as well as system adjustments for increased loads during the summer season. Additionally, scenarios involving an additional water source (well) will be considered to demonstrate its impact on the overall system and its efficiency.
Methodological approaches for obtaining approximate solutions can broadly be classified into three groups: empirical methods, theoretical-analytical methods, and simulation methods. Since this study focuses on the optimization of an existing facility, in collaboration with engineers, certain coefficients were excluded from the calculations. Accordingly, the method applied in this paper belongs to the group of empirical–scientific methods, which are based both on the experience of engineers or project teams and on Nikuradze's experiments and the Moody diagram [11,12].
The objective of this paper is to provide guidelines for improving the Belo Blato water supply system through hydraulic calculations, optimizing its operation, and reducing pressure losses, thereby contributing to better service quality and increased consumer satisfaction. In this hydraulic analysis, several key aspects related to the existing water distribution system in the settlement of Belo Blato will be examined.

REPORT ON THE SPRING SITE INSPECTION

Water demand is determined based on the specific water consumption and the number of inhabitants. Specific water consumption (*qsp*) is defined as the amount of water consumed per capita per day. It is determined primarily on the basis of experience, although in some countries legal regulations exist in accordance with settlement size and the level of household sanitary equipment. In Serbia, it ranges from about 75–200 l/capita/day for villages and around 250 l/capita/day for towns.
The number of inhabitants (*Mk*) depends on local and general socio-economic factors and is not constant over time. It is based on the adopted spatial plan for the designated design period (20–50 years). The average daily water consumption *Qav,d* (l/day) for the population is determined using the following expression [12]:

$$Q_{av,d} = qsp \cdot Mk \tag{1}$$

For the hydraulic dimensioning of water intake structures, the following water quantities are relevant. The maximum daily consumption *Qmax,dn* (l/s) is obtained as the product of the average daily consumption and the daily peak factor [13]:

$$Q_{max,d} = Kd \cdot Q_{av,dn} \tag{2}$$

The maximum hourly consumption *Qmax,h* (l/s), in relation to *Qmax,dn*, is expressed using the hourly peak factor [13]:

$$Q_{max,h} = (Kh \cdot Q_{max,d})/86.400 \tag{3}$$

Table 1. presents the calculated required instantaneous water demand for this settlement.

Table 1. *Calculated required instantaneous water demand [12]*

qk	Mk	$Q_{av,d}$ *[l/day]*	Q_{av} *[l/s]*	$Q_{max,d}$ *[l/s]*	$Q_{max,h}$ *[l/s]*	$Q_{min,d}$ *[l/s]*	$Q_{min,h}$ *[l/s]*
180	1331	239.580	2,77	4,44	8,87	1,22	0,12

For further analysis, we considered a period of 20 years. Figure 1 (left) shows the projected population for this 20-year period. Based on the graph, it can be concluded that in the coming years a natural population decrease of 11% is expected, followed by an additional decline after 2021. At the same time, water demand has increased, as reflected in the maximum daily water requirement for this settlement due to more frequent droughts and the

growing need for larger water volumes. After 2021, a slight decrease in maximum water demand occurred, as shown in Figure 1 (right) [12].

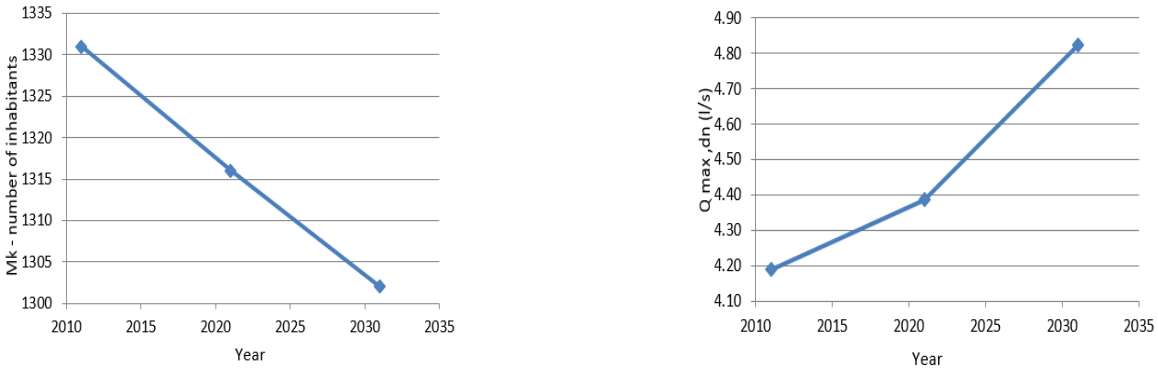


Fig. 1. *Population forecast for the upcoming period (left),Forecast of max. daily water demand (right) [12]*

It is important to note that this calculation was carried out empirically, which means that, in addition to the considerations mentioned in the introduction, the invoiced water quantity for this settlement was not taken into account, and small deviations are therefore possible. Consequently, the actual consumption may be slightly lower during the winter period and somewhat higher than projected during the summer period, when water is used irrationally for lawn, orchard, and garden irrigation.

DATA FOR CALCULATION OF THE EXISTING CONDITION

Water density:

$$\rho \approx 1000 \frac{kg}{m^3}$$

Gravity:

$$g = 9{,}81 \frac{m}{s^2}$$

Pump efficiency:

$$\eta = 0{,}75 = 75\%$$

The pipe lengths and diameters are as follows: for ACC Ø100 mm, length 208 m, made of galvanized steel, with an adopted friction factor of f = *0.02*. The second pipe, ACC Ø150 mm, length 45 m, also made of galvanized steel, has a friction factor of f = *0.018*.
Figure 2 shows the Moody diagram, which presents the flow characteristics. The transitional, or critical, zone is in the range of 2320 < Re < 4000, representing the shift from laminar to turbulent flow and vice versa. Experiments conducted within the transitional zone are considered unreliable [11,12,16].

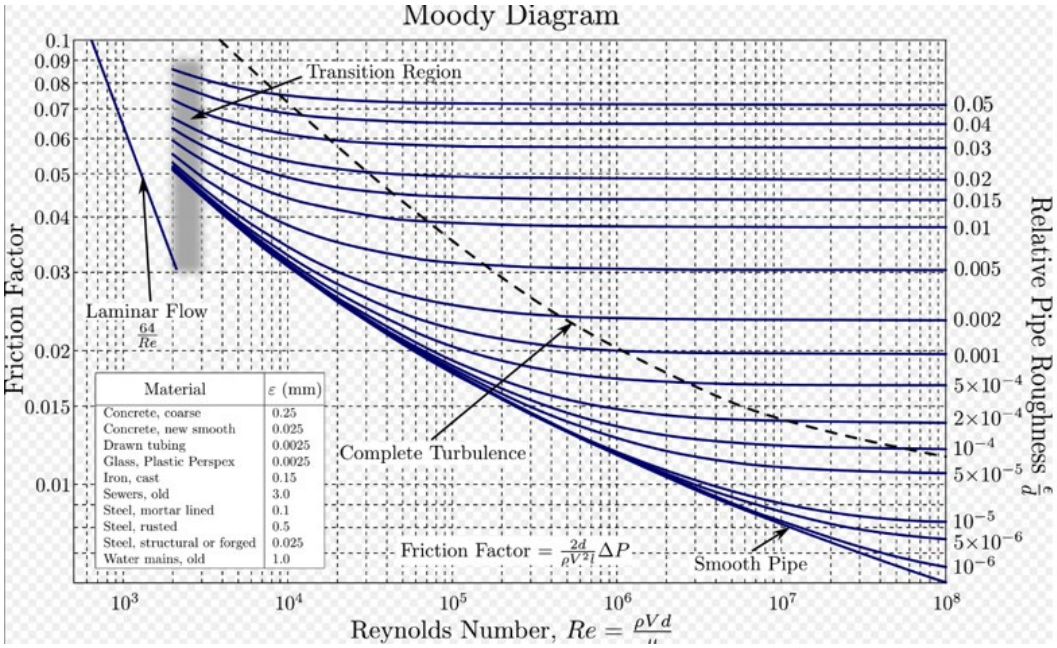


Fig 2. *Moody's diagram [11,6]*

Table 2 presents the characteristics of both pumps, which are centrifugal, underground, and submersible, powered by three-phase current, and operating at pressures ranging from 2.2 bar to 3 bar.

Table 2. *Pump specification [12]*

Pump 1: AP6-F6	**Pump 2: AP6-D9**
Power: 5,5kW	Power: 5,5kW
Voltage: 380V	Voltage: 380V
Current: 14,5A	Current: 14,5A
RPM: 2850min^{-1}	RPM: 2850min^{-1}

CALCULATION OF THE REQUIRED PUMP POWER

Average flow rate: P – pump power [5500W]; H – pumping head [24m].

$$Q = \frac{P \cdot \eta}{\rho \cdot g \cdot H} \tag{4}$$

Losses in ACC Ø150mm pipe through pressure drop: L – pipe lenght [45m]; D – pipe diameter [0,15m]

$$\Delta P = f \cdot \frac{L}{D} \cdot \frac{\rho \cdot v^2}{2} \tag{5}$$

$$v_{150} = \frac{Q}{A_{150}} \rightarrow v_{150} = \frac{Q}{\frac{d_{150}^2 \cdot \pi}{4}} \tag{6}$$

Losses in ACC Ø100mm pipe through pressure drop: L – [208m]; D – [0,1m]

$$v_{100} = \frac{Q}{A_{100}} \rightarrow v_{100} = \frac{Q}{\frac{d_{100}^2 \cdot \pi}{4}} \tag{7}$$

Total pumping head:

$$H_{total} = H + \frac{\Delta P_{150} + \Delta P_{100}}{\rho \cdot g} \quad (8)$$

Required pump power:

$$P_{req} = \frac{\rho \cdot g \cdot Q \cdot H_{ukupno}}{\eta} \quad (9)$$

The obtained values from the previous calculation are presented in Table 3.

Table 3. *Calculated values for required pump power*

The parameters	Values
Q – Average flow (l/s)	17,5
v_{150} – Flow velocity Ø150 (m/s)	0,990
v_{100} – Flow velocity Ø100 (m/s)	2,23
ΔP_{150} – Pressure drop Ø150 (kPa)	2,64
ΔP_{100} – Pressure drop Ø100 (kPa)	103,4
H_{total} – Total head (m)	34,82
P_{req} – Recuired power (kW)	7,97

CALCULATION OF THE REQUIRED PUMP POWER DURING THE SUMMER SEASON

The same parameters as in the previous calculation were processed, except that a 30% higher load was applied due to summer conditions, when temperatures are significantly higher and water is consumed in a considerably more irrational manner. The obtained data are presented in Table 4.

$$Q_{summer} = 1{,}3 \cdot Q \quad (10)$$

Table 4. *Calculated values for required pump power in the summer season*

The parameters	Values
Q_{summer} – Average flow (l/s)	22,75
$v_{150,summer}$ – Flow velocity Ø150 (m/s)	1,29
$v_{100\,,summer}$ – Flow velocity Ø100 (m/s)	2,9
$\Delta P_{150,summer}$ – Pressure drop Ø150 (kPa)	4,493
$\Delta P_{100,summer}$ – Pressure drop Ø100 (kPa)	174,928
$H_{total,summer}$ – Total head (m)	42,29
$P_{req,summer}$ – Recuired power (kW)	12,584

CALCULATION OF PUMP POWER WITH THREE PUMP„B-3"

In the next step, the parameters were calculated in order to determine the operation of the system in the case of adding another identical well, i.e., an additional identical pump. The obtained results are presented in Table 5.

The total nominal flow rate for a single pump:

$$Q_1 = \frac{Q}{2} \tag{11}$$

The total nominal flow rate for a three pump:

$$Q_3 = Q_1 \cdot 3 \tag{12}$$

Table 5.*Calculated values for required power using three pump*

The parameters	Values
Q_1 – Average flow for single pump (l/s)	8,75
Q_3 – Average flow for three pump (l/s)	26,25
$v_{150,3}$ – Flow velocity Ø150 (m/s)	1,49
$v_{100,3}$ – Flow velocity Ø100 (m/s)	3,35
$\Delta P_{150,3}$ – Pressure drop Ø150 (kPa)	5,994
$\Delta P_{100,3}$ – Pressure drop Ø100 (kPa)	233,45
$H_{total,3}$ – Total head (m)	48,4
$P_{rec,3}$ – Recuired power (kW)	16,62

CONCLUSION

An analysis of the existing water supply system for the settlement *Belo Blato* was carried out, leading to the conclusion that the required pump power is 7.97 kW during the non-summer period. After performing calculations for the system under increased demand of 30% during the summer season, when water consumption becomes significantly less rational, the required pump power amounts to 12.584 kW, which cannot be provided by two wells. The specific problems that arise in this case are reflected in pressure drops and insufficient flow.
The actual pumping head of the wells is 24 meters. Based on the calculation with three wells, it was concluded that the required pump power would amount to 16.62 kW, which is sufficient to ensure the water supply of the settlement *Belo Blato* throughout the entire year and under varying weather conditions.
It is important to emphasize that the data used were obtained from the private archives of the company. Furthermore, the invoiced water consumption for this settlement was not taken into account, which may result in slight deviations. Specifically, the actual consumption may be somewhat lower during the winter period or slightly higher than the forecast during the summer period.

REFERENCE

[1] Ryu, Y., Lee, H., E.: Optimal Design of Water Distribution System Using Improved Life Cycle Energy Analysis: Development of Optimal Improvement Period and Unit Energy Formula, Water, 16(22), 3300, 2024.
[2] Laucelli, D., Spagnuolo, S., Rinaldi, A,. Perrone, G., Berardi, L., Giustolisi, O.: DESIGNING ADVANCED ASSET MANAGEMENT FOR WATER DISTRIBUTION NETWORKS: APPLICATION TO A REAL CASE STUDY, 2nd International Joint Conference on Water Distribution Systems Analysis & Computing and Control in the Water Industry, pp. 1057-1072, Spain, Valencia, 2022.
[3] Duan, B., Gao, J., Cao, H., Hu, S.: Energy-Efficient Management of Urban Water Distribution Networks Under Hydraulic Anomalies: A Review of Technologies and Challenges, Energies, 18(11), 2877, 2025.
[4] Alsanad, A., Mahmoud, A., Aljadhai, S.: An Optimal Upgrading Framework for Water Distribution Systems Operation, Water, 16(12), 1737, 2024.
[5] Djordjević, L., Novaković, B., Šeljmeši, D., Landup, D. (2025). Financial Viability and Energy Efficiency of Residential Solar Power Systems: A Case Study from Serbia. In: Karabegović, I., Kovačević, A., Mandžuka, S. (eds) New Technologies, Development and Application VIII. NT 2025. Lecture Notes in Networks and Systems, vol 1482. Springer, Cham. https://doi.org/10.1007/978-3-031-95194-7_79
[6] Hu, S., Gao, J., Zhong, D., Wu, R., Liu., L.: Real-Time Scheduling of Pumps in Water Distribution Systems Based on Exploration-Enhanced Deep Reinforcement Learning, Systems, 11(2), 56, 2023.
[7] Emiliawati, A.: A study of water pump efficiency foe household water demand at Lubuklinggau, PROCEEDINGS OF THE 3RD INTERNATIONAL CONFERENCE ON CONSTRUCTION AND BUILDING ENGINEERING (ICONBUILD) 2017: Smart Construction Towards Global Challenges, 1903, pp.100003-1-100003-10, 2017.
[8] Connencting resporitories, Optimizacija mreža pod pritiskom modeliranih ΔQmetodom, Available at https://core.ac.uk/outputs/219109392/?utm_source=pdf&utm_medium=banner&utm_campaign=pdf-decoration-v1
[9] Martin-Candilejo, A., Santillan, D., Garrote, L.: Pump Efficiency Analysis for Proper Energy Assessment in Optimization of Water Supply Systems, Water, 12(1), 132, 2019.
[10] Ivetić, M.: Računska hidraulika tečenje u cevima, Građevinski fakultet Univerzitet u Beogradu, Beograd, 1996.
[11] Crnojević, C.: Mehanika fluida, Mašinsku fakultet Univerzitet u Beogradu, Beograd, 2018.
[12] Internal archive of the company JKP „Vodovod i kanalizacija" Zrenjanin
[13] Željko, Š., Španja, S.: Vodoopskrba naselja priručnik: primjeri riješenih zadataka iz teorije i prakse, Sveučilište Josipa Jurja Strossmayera u Osijeku, Građevinski i arhitektonski fakultet u Osijeku, Osijek, 2024.
[14] Jones, F., Harris G.: ITS-90 Density of Water Formulation for Volumetric Standards Calibration, 97, pp. 335–340, 1992.
[15] Halliday, D., Resnick, R., Walker, J.: Fundamentals of physics (10th ed., Extended), John Wiley & Sons, Hoboken, New Jersey, 2013
[16] de Souza, M., Paulo R.: A Note on the Moody Diagram,*Fluids*, 9(4), 98,2024.

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WATER 4.0 - DIGITALISATION IN THE WATER SUPPLY AND SEWERAGE SECTOR

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Abstract: Digitization enables companies in the water supply and wastewater treatment sector to adapt to climate, demographic and structural changes. Water 4.0 is the interaction of innovative, current and future network technologies, in which water is viewed as a natural resource, product or raw material with the aim of sustainable management, use and risk reduction, taking into account the interests of all direct and indirect users and stakeholders. Networking of management and measurement systems with solutions for data analysis and modeling leads to obtaining information that supports or provides a basis for decision-making, implementation of measures and monitoring of their functioning in the water supply system. In addition, information gathered over time can provide new ways to ensure more efficient use of water in different application areas. This makes Water 4.0 a holistic approach that evaluates digital data and uses it for predictions, drawing on data from other technical fields, thus enabling sustainable decision-making. The concept of Water 4.0 is not static, but follows technical development and uses new opportunities that are provided. An important feature of the current stage of development of both Industry 4.0 and Water 4.0 is the merging of real and virtual models into cyber-physical systems. This is reflected in the real-time connection of sensors, computer models and controllers to real water systems using smart grids and intranets/internets. The integration of processes, measures and technologies into the IT system is taking place, including classical, proven methods, as well as new, innovative approaches.
Key words: Internet of Things, digital twin, water purification, water supply

INTRODUCTION

The cliché-sounding phrase - life is impossible without water could soon become a gloomy forecast if current statistical trends hold true. Today, 3.6 billion people face insufficient access to water for at least one month of the year. Water scarcity is not only a problem in arid, rural or underdeveloped regions, but is increasingly affecting wealthy nations and urban areas. According to UN-Water, the number of urban residents without safe drinking water has increased by more than 50% since 2000 [1]. Climate change, urbanization, and pollution from agriculture and industry threaten water quality in lakes, rivers, and aquifers in many regions around the world, making clean water an increasingly scarce and valuable resource. According to the Global Water Intelligence White Paper, water networks are responsible for 135 million tons of CO_2 emissions. Reducing this figure by 30% by avoiding leaks would significantly reduce the carbon footprint of water infrastructure. Investing in leak detection technologies often pays off through reduced water losses and energy savings [10]. New technologies can help detect and locate leaks of all types and sizes. Digital solutions provide improved monitoring of water and sewage infrastructure systems and optimized operation of systems and installations. They can ensure compliance with increasingly stringent regulatory requirements for drinking water and wastewater quality, as well as for the safety and quality of supply. By networking and integrating process, engineering and operational data, the entire technical and organizational process and value chain of the water industry can be represented in the form of a digital model. This is the so-called digital twin – a data-driven model that includes all design and operational data for the entire life cycle of the plant. The digital twin supports continuous optimization of design, operation and maintenance procedures. Intelligently linking plant performance data with global data such as weather reports, combined with advanced analysis methods such as machine learning, enables water utilities to optimize day-to-day plant operations and better respond to unusual events (eg heavy rainfall, network leaks, etc.). Such solutions are already available today [11, 12]. One of the applications of digital solutions is the optimization of the electricity consumption of

pumping plants. Pumping water during transport or treatment often requires high-power pumping units that are responsible for a large part of the energy consumed in the water sector. Therefore, optimizing the energy consumption of pumps can help significantly reduce the costs and carbon footprint of water and sewage systems. In addition, the optimized operation of the installations reduces the load on the equipment and increases the availability and service life of the pumps and related components. However, energy-efficient operation should not come at the expense of safety. That is why data must be analyzed in real time, both from installations and from other sources. Intelligent applications such as SIWA Optim collects data from process management systems and links them to utility data, consumption forecasts and other sources. The application integrates all analysis parameters using advanced algorithms, which results in a reduction of operating costs with supply protection and greater resource security [13, 14]. One of the most common causes of water loss around the world is leakage or theft, which represents a major problem for water management. This not only affects the economic performance of water utilities, but also increases pressure on natural water resources. In addition, unreported wastewater leaks are often a major source of pollution and can affect water quality and the state of the environment. For this reason, water utilities must be able to detect and locate leaks quickly and with great accuracy. Using technology similar to that used to detect water on other planets, satellites can provide images that help identify leaks in water systems on Earth. Advanced tools such as the SIWA Leak app use data from existing measurement and automation systems and combine different measurement methods (flow, mass balance, pressure analysis, pressure drops) to detect leaks with minimal delay and high accuracy. In addition, cloud applications such as SIWA LeakPlus combine data from the water distribution network with cloud computing, artificial intelligence and hydraulic simulations to detect hidden anomalies that indicate leaks. Using these digital tools, leaks can be detected faster and more accurately than before, reducing the time and percentage of leaks by up to 50% [11, 12, 15, 16]. Digitization also offers benefits in terms of capacity management, e.g. for sewage systems. These systems are already affected by the effects of climate change. When the surface swelling and sewage are collected in a combined sewerage system, abundant precipitation (for which it is expected to occur due to climate change, especially in Europe) can lead to an uncontrolled discharge of contaminated water into natural water surfaces. Dried, in turn, lead to "dry" pipes in which sedimentation arises, with unpleasant odors from the sewer system. In order to cope with abundant precipitation and insufficient cleansing of the sewer system, the water supply system needs optimized control of pumping plants and adequate capacity of the tank. The intelligently centralized solution for sewage management and control can enable that capacity in the sewer network is used to relieve pipes and flow leveling to wastewater treatment plants. Applications such as Siwa Sewer enable dynamic online optimization of sewerage operation based on current levels in pipes, collected and overflow tanks. Valves and pumps can be managed based on current precipitation forecasts to optimize sewage management and increased wastewater treatment efficiency, preventing uncontrolled sewage discharge in the environment [2, 3, 17]. As these examples show, digitization can contribute to safer drinking water supply and wastewater disposal, reduced energy consumption and lower operating costs. By integrating advanced solutions and services such as digital twins and machine learning, the industry can benefit from applications and digital services that enable greater transparency throughout the plant lifecycle and value chain. In this way, utility companies increase efficiency and savings potential in many areas, while at the same time ensuring a reliable supply. To support these efforts, Siemens has developed a package for the water supply and wastewater industry. Through full application interoperability and comprehensive and flexible plant data analysis in a virtual environment, the MindSphere application increases the availability of information throughout the entire life cycle. The package also includes Siemens Water Applications (SIWA), developed specifically for the water and wastewater industry, combining digitization with engineering expertise [17].

IoT TECHNOLOGIES IN THE WATER AND SEWAGE SYSTEM

The need to adopt innovative technologies such as the Internet of Things (IoT), cloud-based virtualization and modeling are becoming increasingly important, especially in the field of wastewater treatment. Water management is a responsible process in which the margin for error is small. If even one monitoring device in the communication protocol loses connectivity, it can lead to significant water loss or failure of the water network. Reliability and durability of components are of utmost importance, as well as interoperability between sensors and communication transmitters. All these factors must be present for the implementation of remote monitoring to be effective. In the field of water purification, industrial IoT systems find application, e.g. in monitoring chlorine content in water supply networks in real time, monitoring pressure changes in pipes and using ultrasonic sensors for early warning of water supply and sewage operators about upcoming events [2, 3]. Currently, organizations in the water sector depend heavily on Supervisory Control and Data Acquisition (SCADA) systems to monitor certain parts of the water distribution system. However, the practical placement of monitoring points often limits the application of these solutions. IoT advancements in the water sector are helping to improve water management by providing wireless system automation throughout the water network. IoT connects all objects and devices equipped with electronic sensors in a network and allows them to communicate with each other and issue commands to actuators to perform various functions. Implementing Internet connectivity in industrial facilities with dispersed distribution is a particularly challenging endeavor. Industrial IoT (IIoT) devices are typically deployed in remote locations to reach physically inaccessible locations and provide real-time information (e.g., sensors located in remote reservoirs or underground shafts) [4]. These devices must be robust enough to withstand corrosive chemicals, aggressive gases and liquids. In addition, hundreds of sensors may be required in a water system for operators to receive real-time information. Each sensor requires a reliable power supply and communication network to operate continuously. Accessibility is also a challenge in many cases – e.g. in order to build a network to monitor hydrogen sulfide (H_2S) in the sewage system, the sensors must be powered by long-life batteries. Failure to do so will result in increased maintenance costs. The physical presence of personnel responsible for monitoring activities in wastewater treatment plants will always be necessary, but this accounts for 30% of the operating costs of a treatment plant. New IoT technologies take advantage of automation to reduce the need for operator involvement. Water management uses the concept of smart sensors installed at various points in the water supply system. They can collect data and send it back to tracking systems. With the help of smart IoT technology implemented in multiple components of the water network, it can also be ensured that losses are reduced. The implementation of this new technological approach is in some cases conditioned by regulatory requirements. The concept of IoT technologies in water purification is based on a reliable communication system that is used to wirelessly send data from physical objects to a computer connected to the cloud, which has the appropriate software to analyze this information. Through smartphone and tablet apps that connect to the cloud, water utilities can access real-time data from IoT sensors. These mobile devices can, e.g. provide useful information about the entire network to technicians, engineers and other personnel responsible for managing water treatment plants [4, 5]. With smart leak detection sensors, faults such as burst pipes can be located quickly and easily. When a leak is detected, the sensors generate an immediate warning and send it to the remote control panel. Thanks to timely corrective measures, damage can be prevented and limited, thereby reducing losses. IoT technologies are also used in wastewater treatment through smart sensors to measure the amount of chemicals remaining after treatment. The information they provide can be used to calculate the effectiveness of the selected treatment process and ensure that the amount of chemicals released remains within acceptable limits. This network of sensors and communication technologies for smart water management enables companies to take advantage of big data analytics, cloud storage and mobile computing, contributing to practical improvements and cost reductions. The introduction of IoT in the water sector allows the operational centers of

water management and monitoring systems to be located anywhere [11, 12]. Water management costs can be reduced by improving equipment utilization, process efficiency and productivity, as well as improving services. Monitoring the pressure in water supply networks enables the prevention of accidents and the limitation of losses and damages in the event of bursting and leaking pipelines. Water utilities can use pressure monitoring to ensure that the pressure value in the water supply system is as low as possible. In addition, optimized pressure helps optimize the operation of pumping stations, which leads to a reduction in energy consumption. On the other hand, pressure monitoring ensures efficient water flow management and prevents a possible increase in the amount of water discharged into the sewer, bringing the water supply system in line with the requirements of regulatory authorities. Also, modern remote monitoring solutions based on IoT technology are significantly cheaper than their predecessors. Other benefits of IoT technologies for the water sector are more efficient maintenance and improved service. Appropriate data analysis programs can significantly help companies in making decisions and developing preventive and predictive maintenance strategies. This can include e.g. measuring total chlorine content in remote tanks to facilitate timely mixing or dosing of chemicals to prevent nitrification, or determining groundwater levels and conductivity to properly model underground aquifers and prevent potential disasters. These benefits further improve network performance and help achieve additional cost savings. A more efficiently managed water network provides better service to customers by ensuring consistent system pressure, fewer interruptions in water supply, and proper chlorination.

CONCEPT OF WATER 4.0 IN LIGHT OF INDUSTRY 4.

The importance of digitalization is constantly growing, with popularization of terms such as big data, Internet of Things (IoT), industrial IIoT and cyber-physical systems (CPS) [4]. The water industry is constantly looking for opportunities to adapt to changing boundary conditions, as well as to find effective solutions to face global challenges in this area. Climate change and urbanization, just two of the important driving forces in the water sector around the world, are continuously increasing the demand for water resources that are diminishing. Water 4.0 is a concept that has recently been accepted as the future of the water industry. But in order to explain the essence of this concept, the principles of Industry 4.0 must first be considered. Industry 4.0 is a collective term for technologies and concepts related to organizing value chains. Based on the technological concepts of cyber-physical systems, the Internet of Things and the Internet of Services, Industry 4.0 helps realize the vision of a smart factory. Within modularly structured smart factories, cyber-physical systems monitor ongoing processes, create virtual copies of the physical world and make decentralized decisions. These systems communicate and collaborate with each other as well as with people in real time via IIoT. The concept of Industry 4.0 is based on six principles:

• interoperability – the ability of cyber-physical systems (ie devices that participate in the production of certain elements, assembly lines and products), people and smart factories to connect and communicate with each other through the Internet of Things and the Internet of Services;
• virtualization – a virtual copy of a smart factory, created by connecting data from sensors that detect physical process parameters with virtual and simulation models;
• decentralization – the ability of cyber-physical systems to make decisions on their own;
• real-time monitoring – the ability to acquire and analyze data and provide immediate conclusions;
• service orientation – offering services (cyber-physical systems, people and smart factories) through Internet services;
• modularity – flexible adaptation of smart factories to the changing requirements of individual modules [7, 8]. All concepts from Industry 1.0 to 4.0 refer to the manufacturing industry, which is relatively simple: something is made and assembled using separate parts. At the forefront of the concept of Water 4.0 are digitization and automation, and the goal is efficient, flexible and competitive management of water resources. Water 4.0 provides a high degree

of transparency for users, thereby covering current needs and providing opportunities for sustainable activities in water management. The implementation of Water 4.0 through cyber-physical systems achieves the optimal connection of virtual and real water systems, where planning, construction and operation are largely done by software.

REALIZATION OF THE WATER 4.0 CONCEPT

The realization of the Water 4.0 concept (intelligent water management or simply efficient exploitation of water resources), which is necessary for the future of the sector, can be achieved by applying the basic principles of Industry 4.0. Figure 1 shows the configuration of the water supply system according to the concept of Water 4.0 [18].

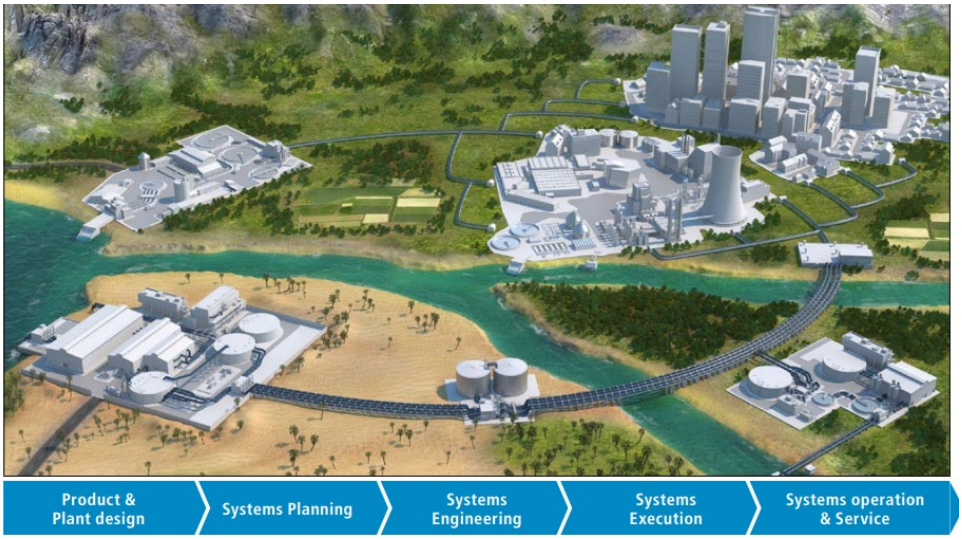


Fig. 1. *Water 4.0 - Sketch of a complex water supply system (source Siemens)*

There are several barriers to successful implementation of the approach that need to be considered not at the company level, but at the industry level as a whole. The first of these obstacles is related to communication protocols - until now, water and sewage systems have mainly worked with analog signals and Profibus protocol in larger installations, and future concepts are more focused on Ethernet [7, 8]. A large number of technical and technological units that are part of a water supply system (sources, dams, river intakes, well plants, reservoirs, pumping plants, transport pipelines, etc., often distributed over large areas and distant locations from each other) have sensors for measuring various process variables and parameters (level, pressure, flow, temperature, concentration of harmful elements such as manganese, iron, arsenic, etc., chemicals - chlorine, fluorine, aluminum sulfate). Advances in sensor technology and wireless communication protocols have enabled the application of IoT in various industries. This is also the case with the water supply and sewerage sector. Data from the sensors are sent via wireless networks to base stations. In recent times, the LoRa (Long-Range) protocol has gained increasing popularity and application. Hundreds of millions of IoT devices in more than a hundred countries are connected in the LoRa network communication system, which enables data transmission over long distances (up to 10 km) with low energy consumption. According to forecasts, over 50% of IoT devices will use the LoRa protocol by 2026. LoRa works with a spectrum of frequency bands. In our country, the frequency bands 433 MHz and 868 MHz are used, and no special licenses are required if the maximum permitted transmission power is not exceeded. LoRa supports the use of different bandwidths starting from (7.8 kHz to 500 kHz), which enables the operation of a larger number of independent networks in different parts of the frequency band. The data transfer speed is proportional to the bandwidth. The highest transmission speeds are achieved by using a bandwidth of 500 kHz, but in this case, a maximum of two to three independent

networks per frequency band is possible. The range of wireless communication between the transmitter and receiver depends on the loss in the signal propagation path. These losses increase with the square of the distance in a clear space, while in mountainous or urban areas due to various obstacles the losses increase significantly faster, with an exponent ranging from 3 to 5 [4]. Cybersecurity as a problem is becoming a very serious issue in the water industry. Ensuring complete security is an absolute necessity for anyone using a cloud or IoT environment. The problem becomes even more important and relevant in view of hacker attacks. Such attacks related to e.g. chemical dosing can have a serious impact on water service users or the environment [9]. The third challenge for implementing the concept is the quality of the tools and data and eliminating the situation in which there is a lot of available data, but no useful information is extracted. Water utilities have a variety of equipment and devices that generate a huge amount of data, which does not always provide a basis for taking the necessary actions. Therefore, it is necessary to move to an approach that ensures the availability of rich and accurate information, but in an understandable and easily accessible format. This of course requires the investment, installation, management and proper maintenance of appropriate equipment. Water 4.0 offers enormous potential for optimizing the management of water infrastructure systems and achieving rational and more efficient use of resources (eg energy, water, manpower), combined with improved security of water supply and wastewater treatment. Studies show that the key point in networking and automating the water infrastructure is related to the education, training and skills of all employees involved in the creation of value. In order to meet the new requirements, it should be determined exactly what skills are needed and how to improve the knowledge of the subjects involved. In the future, both experienced and newly hired staff will have to deal with the new situation, with the need for education and training to focus on current challenges. The implementation of Water 4.0 is an evolutionary process – existing basic technologies and expertise must be adapted to the special needs of the water industry, especially in an international context.

DIGITAL TWINS IN WATER SUPPLY AND SEWAGE SECTOR

In their efforts to provide reliable, stable and affordable systems, water supply and sewerage companies face problems such as rising electricity prices, depreciating infrastructure, water shortages and losses, natural disasters related to climate change, etc. The solutions to these problems are equally numerous and diverse – from public-private partnerships to awareness of the need to preserve water resources and the application of smart technologies. The availability of quality data is of fundamental importance for making optimal decisions. Companies in the water supply and sanitation sector are striving to find an efficient way to use the data they already have and that is collected regularly, often isolated in disjointed IT solutions, spreadsheets and paper records. Digitization of data and the business processes it supports can help the mentioned companies to make maximum use of data when making decisions, increase the efficiency and quality of the services they offer. One of the most powerful tools in this area is digital twin technology. Figure 2 shows the role of a digital twin in the creation of a modern water supply system [19]. A digital twin is a virtual representation of physical equipment, processes or systems. Creating a digital twin of the water supply and sewerage system involves the integration of virtual engineering models with real models and GIS data. In addition, digital twins are continuously updated with operational data from SCADA systems, sensors, meters, etc. This is what distinguishes digital twins from static 3D models. The end result is an intelligent and connected digital infrastructure model that supports the planning, design, construction and operation of smart water and sewer networks. Digital twins of water and wastewater systems provide accurate and reliable data that businesses can use for "what-if" analyzes and decision-making throughout the system's lifecycle – from long-term forecasting e.g. capacity to direct monitoring of operational parameters and response in the event of an accident. By introducing a model of the system's hydraulic characteristics and water quality that reflects existing conditions, digital twins enable the simulation of events such as pipeline failures, power outages, fires, pollution, etc.

As a result, water companies can analyze the resilience of their systems and assess the corresponding risks.

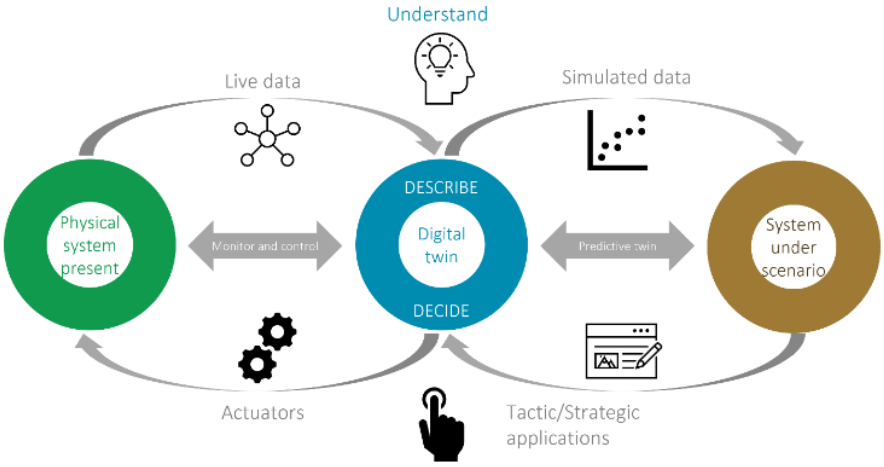


Fig. 2. *Digital twin diagram, with the left side representing operational applications (present) and the right side tactical and strategic applications (what if and future scenarios)*

Digital twins effectively use data from different management systems, thereby supporting strategic management of equipment based on risk assessment. These advantages contribute to optimizing costs, extending the life of equipment and prioritizing certain projects in order to improve performance [7, 8]. Continuously updating digital twins with the latest operational data helps utilities locate potential leaks and reduce water loss. Most water utilities already have a hydraulic model of their system, which is used for planning and design. By integrating hydraulic models with data from the SCADA system, digital twins enable the determination of properties of the water supply system that cannot be directly measured. This provides a more complete view of the system, which can help increase safety and reduce breakdowns (eg pipeline bursts).

CONCLUSION

With the advent of digitization, more and more procedures, tools and other resources are becoming available, contributing to a new era in water management. Like other industries, the water industry is able to further improve its future competitiveness with modern automation. Through the increased implementation of IT technologies, sensors and modeling applications, opportunities are created for a better understanding of water management systems in terms of their complexity. The integration of planning and work processes with the help of intelligent hardware, software and independent exchange of information (from consumers to individual components to water supply and sewage companies) is becoming increasingly necessary to achieve high productivity and efficient use of resources. IoT and services also play an important role in these real-time systems, making data about water-related processes and characteristics more durable, accessible and usable whenever and wherever needed. It is also possible to further network other data (eg short-term and long-term weather information) to prepare forecasts that can be fed into control algorithms for processes in the water sector. Choosing the right communication network is also not easy, due to the number of competing networks available in the market. Although modern IIoT technologies make remote monitoring of remote locations more affordable compared to legacy telemetry solutions, the investment in them is significant. A positive fact is that the investment return period is approximately one year. However, the online infrastructure itself poses a threat to the security of water companies' equipment and is associated with the risk of misuse. The Internet of Things can be one of the most important approaches in the development of management of utility systems, which will contribute to a more efficient use of water resources. IoT solutions for water monitoring and management provide the ability to

collect data from a large number of devices, analyze and send data or processed results to different applications or other devices, which enables optimization of the management process and prevention or limitation of possible accidents.

REFERENCES

[1] Stankov, S., Control of Pumping Stations in Water Supply Syst*ems*, časopis „Voda i sanitarna tehnika", ISSN: 0350–5049, Izdavač: Udruženje za tehnologiju vode i sanitarno inženjerstvo Beograd, godina XLI, br. 3-4, str. 47–54, 2011.
[2] Stankov, S., Sistem nadzora i upravljanja postrojenjem za prečišćavanje vode, časopis Vodoprivreda, ISSN 0350–0519, Izdavač: Srpsko društvo za odvodnjavanje i navodnjavanje, Beograd, vol. 50, broj 4-6, str. 319-332, 2018.
[3] Stankov, S., Water Purification in the Process Industry, Trideset sedmi međunarodni kongres o procesnoj industriji PROCESING 24, Beograd, 29–31 maj, Zbornik radova, Izdavač: SMEITS, DOI: 10.24094/ptk.024.121, str. 121–140, 2024.
[4] Stankov, S., Modern Concepts of Supervisory Control Systems Based on PLC and SCADA Configuration, Part of the book New Trends in Engineering Research 2024, Publisher: Springer, Cham. DOI: 10.1007/978-3-031-78635-8_24, **v**ol. 1216**,** pp. 289–313, 2024.
[5] Stankov, S., Savremen način upravljanja procesom proizvodnje mineralne vune, časopis Hemijska industrija, DOI: 10.2298/HEMIND120428069S, Izdavač: Institut SANU, Beograd, Srbija, vol. 67, br. 2, str. 375–384, 2013.
[6] Stankov, S., Big Data in Water Supply and Sewerage System**,** journal Acta Technica Corviniensis–Bulletin of Engineering, ISSN: 2067–3809, Publisher: Faculty of engineering Hunedoara, Romania, Tome XV, Fascicule 1, pp. 21–25, 2022.
[7] Stankov, S., Automation and Industry 4.0**,** Journal Acta Technica Corviniensis–Bulletin of Engineering, ISSN: 2067-3809, Publisher: Faculty of engineering Hunedoara, Romania, Tome XIV, Fascicule 2, pp. 59–63, 2021.
[8] Stankov, S., Development of Automation in the Direction of Hyperautomation**,** Journal Annals of Faculty Engineering Hunedoara–International Journal of Engineering, ISSN: 158-2665, Publisher:, Faculty of engineering Hunedoara, Romania, Volume XXI, fascicule 1, pp. 179–184, 2024.
[9] Stankov S: Security and protection of supervisory control systems in light of industry 4.0, 19th International Conference "Man and Working Environment"–Occupational and Environmental Safety Engineering & Management (OESEM), Proceedings, ISBN 978-86-6093-112-4, Publisher: Faculty of Occupational Safety, Niš, pp. 299–306, 2022.
[10] https://assets.new.siemens.com/siemens/assets/api/uuid:782cf8bb-2fe7-4232-9b0e-49a7fbcc2b64/vrws-b10003-00onepagerdigi-waterleakenus-144.pdf
[11] https://www.iwra.org/wp-content/uploads/2024/03/Bora-Helvaci_IWRA-digital-transformation.pdf
[12] https://www.vertexgrp.com/solutions/water/ai-monitoring/
[13] https://plm.sw.siemens.com/en-US/insights-hub/
[14] https://www. .com/us/en/industries/water.html
[15] https://www.siemens.com/global/en/products/automation/industry-software/digital-applications-and-services-for-process-industries.html
[16] https://www.youtube.com/@SiemensKnowledgeHub
[17] https://www.sw.siemens.com/en-US/
[18] https://germanwaterpartnership.de/wp-content/uploads/2019/05/GWP_Brochure_Water_4.0.pdf
[19] https://www.kwrwater.nl/en/projecten/digital-twins-for-the-water-sector/

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WATER LOSSES IN THE WATER SUPPLY PROCESS – IDENTIFICATION AND CONTROL

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Abstract: Large losses in the water supply system are a significant problem for water supply companies in our country. In a significant number of water supply systems, more than half of the drinking water is lost during use. There are many reasons for this, the most obvious being an outdated water supply network and leaks in the network. In addition to the loss of a large amount of water, leaks in the system can also lead to water pollution in the network, damage to buildings and equipment, etc. Proper leakage management is one of the most important ways to tackle the problem of water loss. Leakage management is usually associated with pressure control and leakage localization. Various software solutions are used, with input data including the volume of water supplied, billed and metered consumption and average working pressure. Such software solutions cannot replace comprehensive monitoring, but they are a good way to start a control program, as the software calculates various actual and apparent water losses and performance indicators based on the data entered by the user. The automation of water supply and wastewater systems enables optimal distribution based on real-time data and ensures more efficient water use, especially in water-scarce regions. Predictive maintenance features reduce operating costs by identifying potential problems before they lead to costly repairs. This proactive approach increases the lifespan of the infrastructure. Simple and convenient mobile applications allow users to access water consumption data, raise awareness and encourage responsible consumption behavior. By minimizing water loss and increasing the efficiency of water use, the innovative methods contribute significantly to environmental sustainability and help preserve natural resources and ecosystems.
Key words: water losses, leakage, location, pressure control

INTRODUCTION

Today's technological challenges in urban water supply and sewerage require integrated approaches, including advanced methods of water purification, monitoring and management of water resources, and the active involvement of smart buildings and urban residents in this process. These innovations and technologies improve the quality and efficiency of water supply and wastewater systems and ensure a sustainable future for the urban environment [1]. In today's conditions, urban water supply and sewerage are crucial, as they not only ensure the comfort and hygiene of the population, but also the preservation of public health and compliance with environmental standards. The development and maintenance of these systems is a complex process that involves many technological challenges and requires innovative approaches and solutions [2]. New technologies offer the opportunity to improve the efficiency and reliability of urban water and wastewater systems, but also place new demands on management and adaptation. The main challenges are: outdated infrastructure, the need for sustainable management of water resources, the preservation of drinking water quality, the integration of smart management and monitoring technologies, and financial and operational constraints. Global events such as urbanization, climate and demographic change are putting increased pressure on water resources and infrastructure, further exacerbating the above challenges. Infrastructure obsolescence in the water and wastewater sector is a complex problem that affects many aspects of management. Many of the existing water and wastewater systems were planned and built in the post-war period and have only been partially renovated and modernized since then. This leads to an increased frequency of breakdowns, water losses due to leaks, reduced efficiency of treatment plants and ultimately an increased risk of pollution of water resources and the environment. Over time, the materials that make up pipes and other system components are subject to wear and corrosion, which reduces their reliability and increases the likelihood of breakdowns. Many

systems that were designed in earlier times to meet the needs of settlements and industry are no longer sufficiently efficient today. Growth and urbanization lead to an overload of the existing infrastructure. At the same time, leaks in the old infrastructure are the cause of considerable water losses, which not only increase operating costs but also reduce the efficiency of the entire system. Solving all these problems requires an integrated approach that includes both technological innovation and strategic planning. SCADA and IoT (Internet of Things) monitoring of water and wastewater systems through continuous pressure and flow monitoring registers losses and simultaneously sends alarm alerts to dispatch centers. The combination of these methods provides a non-destructive approach to locating leaks with high accuracy and minimal cost. Implementing smart IoT sensors and monitoring systems helps to detect leaks and failures in real time, enabling faster and more efficient intervention. Remote control and automation also offer opportunities to optimize work and reduce water loss [3-5]. On the other hand, establishing long-term programs to renew and replace old infrastructure is critical to improving the reliability and sustainability of water supply and wastewater systems. Informing and engaging the public about the importance of investing in water infrastructure can also support efforts to secure the necessary funding and support for reform. Water resource management is another important aspect as water scarcity becomes an increasingly pressing issue in many regions of the world. Technologies for the efficient use and recycling of water as well as innovations in this area offer solutions to this problem, but also require considerable resources and adaptation to local conditions. The modern management of water resources requires a complex and integrated approach, especially against the backdrop of increasing global demand for water, climate change and urbanization. In this regard, technological innovations and digital capabilities play a key role in optimizing the use, monitoring and management of water resources [4, 5]. Digital twins, IoT technologies, automation, data collection and analysis offer new opportunities to increase the efficiency and sustainability of water supply systems. Digital twins as virtual replicas of physical systems enable the simulation, analysis and optimization of their work in real time. They can be used to model water networks, treatment plants and other key components, providing useful information on potential efficiency improvements and reducing the risk of failures. Through continuous monitoring and analysis, digital twins help predict system behavior under different conditions, making management and maintenance easier. IoT technologies are transforming the management of water resources by enabling the continuous collection and analysis of data from multiple sensors in the water network, treatment plants and other critical points. This gives a detailed overview of the status of the system in real time, including leak detection, water quality monitoring and optimization of pumps and other devices. The integration of IoT with automated management facilitates the implementation of effective strategies to allocate water resources, reduce water loss and improve overall operational efficiency. Automation, supported by advanced data analytics, enables water utilities to optimize their decisions based on in-depth analysis and predictions. Machine learning and artificial intelligence algorithms can analyze vast amounts of data for trends, anomalies and potential threats and make suggestions for effective management. This includes automatically regulating water flow based on demand, predicting maintenance needs and optimizing the treatment process [2, 4-8].

DRINKING WATER QUALITY

The quality of drinking water is of crucial importance for public health. Problems such as pollution from industrial and agricultural sources require the development and application of advanced treatment and monitoring methods to ensure the safety and quality of water. Advanced treatment and monitoring methods provide the opportunity to explore innovative approaches and technologies that are critical to maintaining high drinking water quality and protecting public health. These methods include physical and chemical processes as well as biological technologies and are supported by advances in sensor technology and real-time water quality monitoring data. Drinking water treatment methods are costly solutions and their use is only justified in the presence of certain contaminants [1, 2]. Therefore the

availability of adequate information on potential contaminants is crucial for the efficient operation of drinking water treatment plants. In this regard, modern sensors enable continuous monitoring of water quality by measuring chemical, physical and biological parameters in real time. Sensors can detect a variety of contaminants such as heavy metals, organic compounds and microorganisms, enabling a rapid response when problems are detected. The integration of IoT devices and cloud technologies into water monitoring systems enables remote monitoring and analysis of data from multiple locations, contributing to efficient resource management and water pollution prevention [1, 2]. Artificial intelligence and machine learning offer the ability to analyze large water monitoring data, detect patterns and predict potential risks to water quality. These technologies can improve the accuracy of monitoring and the efficiency of water quality management solution. Technological innovations offer new opportunities to solve today's water supply challenges and provide access to clean and safe water for population on a global scale [3, 6].

IMPACT OF SMART BUILDINGS

With emergence of smart buildings, prerequisites are created for optimizing and increasing the quality of water supply and sewage systems in urban areas. Smart buildings use advanced water management systems that include sensors and automated consumption control. These systems can identify and prevent leaks, regulate consumption in real time and direct the use of recycled water e.g. in toilets, for watering green areas, etc. This reduces the total consumption of water in the city and increases the efficiency of the city's water systems. Smart buildings can reduce their dependence on central water systems by integrating rainwater harvesting and recycling technologies, which reduces pressure on urban water and sewer networks, especially during drought or high consumption, and enables sustainable management of urban water resources. Smart buildings can also include water pretreatment systems that improve water quality even before it is used in the building. This not only ensures a higher quality of life for residents, but also reduces the burden on the city's treatment plants, because the wastewater returned to the system is less polluted. Systems in smart buildings can be integrated into a wider network of smart city systems, sharing data and information about water consumption and quality, thereby enabling city governing bodies to obtain useful information for resource planning and emergency response in real time, leading to more efficient and sustainable management of city water supply and sewage systems. By optimizing water consumption, reducing pressure on infrastructure, improving water quality and integrating with smart city systems, smart buildings contribute to sustainable development and improvement of life in urban areas. City dwellers have a very important role in the sustainable management of water resources, as their daily habits, awareness and engagement can have a major impact on water consumption and quality. Citizen participation in water conservation, recycling and waste water management programs is important for reducing pressure on city water systems. User awareness of the impact of their actions on water resources and support for investments in smart technologies and sustainable practices can help improve the quality of water supply and sewage systems. Modern cities are increasingly resorting to intelligent solutions for monitoring water supply and water distribution to ensure that citizens and industrial enterprises have access to the required quantities of water. The goals of intelligent water resource management are twofold: minimizing losses and wastage due to leakage, as well as rational management of consumption. Although various strategies and programs to reduce water losses and water supply management are implemented in many places around the world, losses due to inefficient distribution and leakage are still a serious problem in the water sector. The European Environment Agency predicts that by 2030, global water needs will increase by as much as 40 percent. Modern smart technologies and mobile applications provide powerful tools for involving city residents in water management processes, promoting sustainable habits, raising awareness and improving the overall efficiency of city water systems. Mobile apps allow users to monitor their water consumption in real time providing useful information that can help identify unnecessary consumption or leaks. The aforementioned applications

can send alarm messages when consumption is extremely high, encouraging a quick response and preventing water loss. Also, applications and platforms that send notifications about emergencies or planned water outages help residents prepare and manage their resources more effectively [3]. A block diagram of a complex intelligent system of water supply and sewerage, which is connected to a cloud platform, is shown in Figure 1 [9].

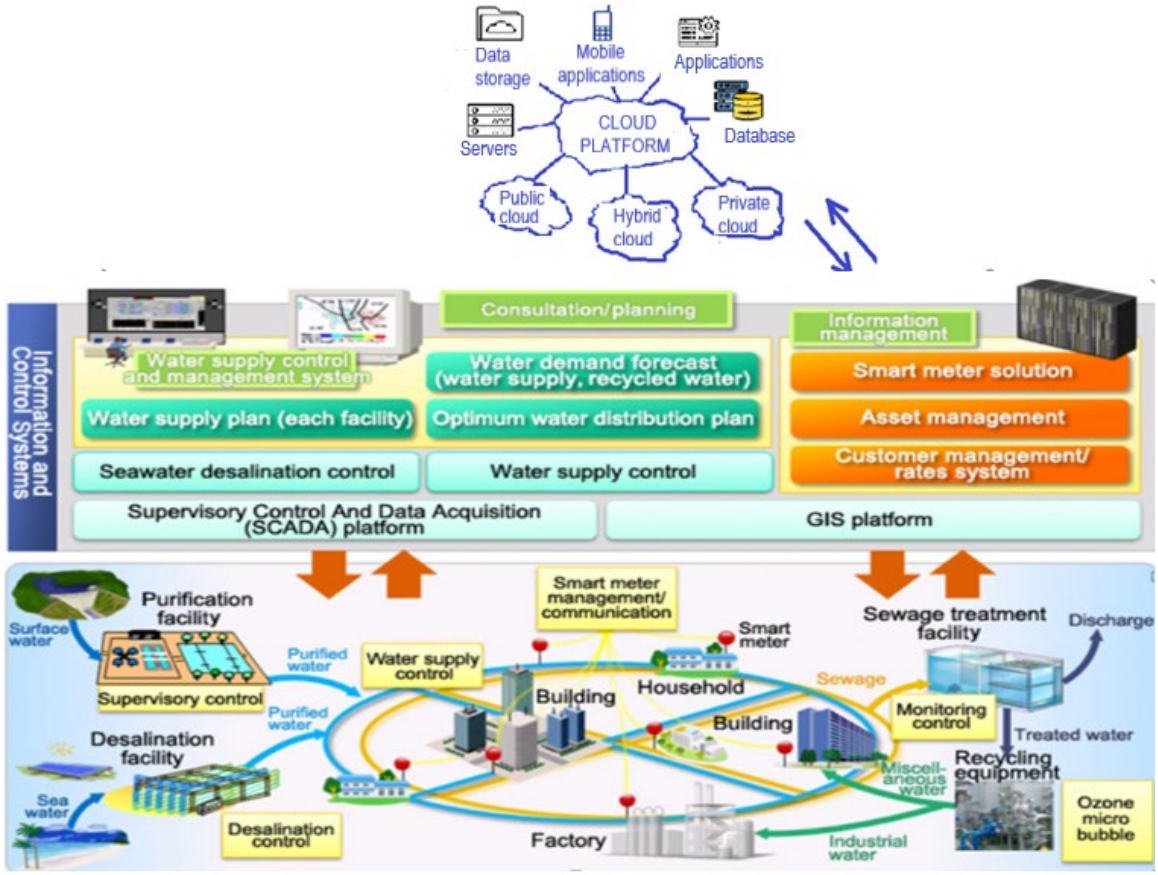


Fig. 1. *Water management system technology*

An intelligent water supply network is a fully integrated set of components and solutions that, based on a large amount of collected data, enable water companies to optimize all aspects of water distribution, waste water collection and treatment systems [9]. The 5-layer model of intelligent water networks is most often considered. The first layer includes physical components-springs, dams, reservoirs, pipelines, pumping stations, well facilities, reservoirs, break chambers, etc. In the second layer are devices and equipment in the field: sensors that measure various parameters such as flow, pressure, level and quality of water, as well as remotely controlled devices such as pumps, various electric drives, regulation and on/off valves. These automation elements are installed in the aforementioned plants of the first layer. In the third layer, data acquisition and communication are performed. There are included systems for storing and transmitting data from remote locations, and this data is forwarded to the layers where it is analyzed and processed. Using two-way communication channels, commands are sent back to the second layer requesting the sensors to collect certain data and commands to the executive bodies (actuators). Part of this layer are e.g. fixed cable network, radio, mobile, Wi-Fi and other communication technologies used for data transmission. The fourth layer includes data management and visualization, whereby collected data is processed and displayed on an operator-friendly interface Supervisory Control And Data Acquisition (SCADA), geographic information system (GIS) or other network visualization platforms. This layer also interacts with systems and tools related to cybersecurity and to support business functions such as order management and customer

information systems. The last, fifth layer applies tools that integrate software for data analysis and modeling using communication channels and sensors in the network. As a result, water companies can automatically remotely manage the network, including monitoring the quality of water in the network, automated leak detection, optimization of pump plant operation, and more. To solve the tasks in this layer, the capabilities of Artificial Intelligence - AI, management and analysis of Big Data, real-time monitoring, Soft Computing that uses fuzzy logic, artificial neural networks, genetic algorithms in the field of evolutionary computing and techniques based on the application of rough set theory can be additionally used [3-6]. These solutions are introduced to enable assessment of the potential impact of changes in the network, to react in time and to consider likely scenarios. To illustrate, an example of modern water resource management in the city of Indore, India is given. By applying edge computing, IoTstar series ICP DAS intelligent controllers, and IIoT cloud infrastructure management software, data on water supply systems located in the aforementioned city can be wirelessly transmitted in real time to a central monitoring and control system via a 4G network, enabling remote management and monitoring of water supply throughout the city [10]. Status of the water supply system can be monitored at any time through operator panels, and the information obtained can be used as a reference for preventive maintenance of the water supply system (Figure 2) [10].

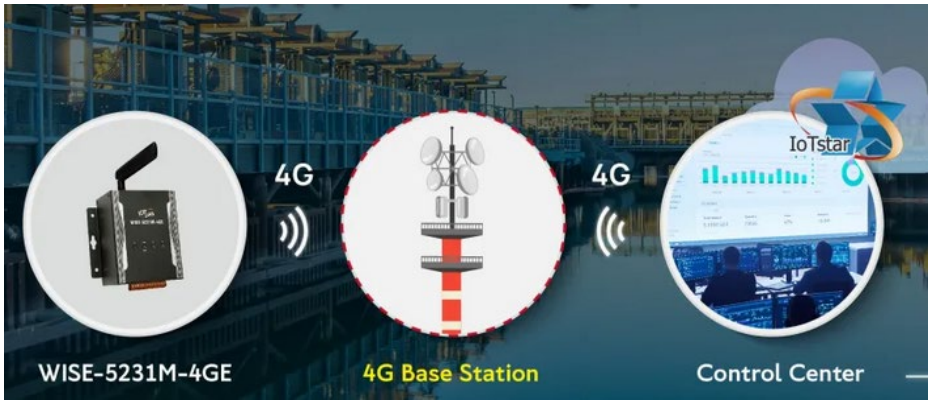


Fig. 2. *Illustration of supervision and control of the water supply system of the Indore city, India*

WATER LOSSES CONTROL

Main reason for large losses is usually an outdated water supply network and numerous breakdowns. However, replacing the water supply network requires significant financial resources, which the water supply companies could hardly provide on their own. In order to overcome the problem of large water losses, in addition to replacing the outdated pipeline network and performing the necessary repair work, it is necessary to undertake other measures related to the management of leaks in the system. Performance and profitability of the water transportation system depends to a large extent on transporting the water with as little loss as possible. Leaks in pipelines mean not only the loss of potable water that has been treated at high cost, but also the potential economic loss caused by possible consequential damages, especially due to the collapse of buildings. Therefore, the goal is to detect and locate leaks in transport pipelines. Leaks can cause serious financial losses to the water supply system. For example a breakthrough of 5 mm at a pressure of 5 bar generates annual losses of about 12.000 m3. With an average consumption of 160 liters per day, this amount is enough to provide the annual drinking water needs of around 200 people. Leak management activities are related to pressure management and finding leak locations. One method used to estimate the amount of water lost through the network is to measure the minimum night flow. In this case, the hourly amount of water delivered to the network is measured during the period when there is the least demand, usually between 1 and 4 at night. Consequently, in parts of the network where leaks are well controlled, the value of the

measured minimum night flow would not be much above zero. The higher the minimum night flow, the higher the leaks in the system.

LOCALIZATION AND LEAKS DETECTION

Bearing in mind that the preliminary analysis provides an overview of the leakage in the network as a whole, the most efficient approach from an economic point of view is to identify and locate the 20% of the largest leaks, since in principle they account for 80% of the losses. A common strategy is to zone the water supply system, which allows the most serious leaks to be isolated to a specific area, which can then be more accurately assessed using appropriate leak detection equipment. Strategically installed flow meters divide the network into specific sectors or zones that can be analyzed independently. Leak detection equipment includes basic and relatively simple technologies as well as more sophisticated ones. One of the simplest devices is a sound detector (microphone). In practice, it is a microphone that is placed on the ground. Microphone amplifies the noise created when pressurized water comes out of a damaged pipe. Finding the location with the loudest noise indicates where the leak is most likely. Advantage of digital microphones is that they distinguish the actual leak noise from the surrounding noise. There are electronic sound detectors for recording and amplifying sound oscillations of all kinds that arise in the very structure being examined. Such a detector is Stethophon 04. Oscillatory sensor enables sound reproduction without distortion even when the noise is barely audible. A ground microphone can be connected to the Stethophon 04 detector to listen to sounds below the ground. The filtering function allows users to listen to the sound at a frequency that best suits their hearing and the noise being heard. Filters make it easier to listening certain noises such as the deep sounds characteristic of leaks from plastic pipes and the higher frequencies from metal pipes. The operator's hearing protection function automatically ensures that the headphones are turned off when loud noises suddenly occur. To facilitate the leak location process, the digital display shows not only the current lowest noise, but also the lowest measured noise from the previous location, so the operator can see if he is moving closer or further away from the sound source [11]. In addition, to measure an accurate digital value in real time, the noise level is represented graphically. By recording noise levels for several locations, the location of the leak can be determined with high precision. There are more complicated devices - noise correlators. In principle, correlation is the detection of leaks based on a computational process for underground pipelines with flow. Noise caused by the leak propagates along the pipe and reaches the two fittings (valves, hydrants, fire hydrants, etc.) at different times depending on the distance from the leak to the contact points. Highly sensitive sensors are used that detect the resulting noise from the fitting, and the radio transmitter forwards them to a receiver (correlator) that determines the location of the leak by calculating the time difference based on the different distance between the contact points and the leak. In order to more precisely determine the location of the leak, it is necessary to take into account the material, diameter and length of the measured part of the pipeline. With use of a correlator, the leak can be located with a precision of up to a few centimeters. Intensity of the background noise has no influence on the measurement results.

CORRELATION FUNCTION

Conventional correlators require a highly skilled operator to search the required data in the software, including the material, diameter and exact length of each pipe segment between the sensors. The quality of the results depends largely on the operator's ability to obtain a clean correlation peak using manual adjustment of the filter range. The decision as to whether or not a leak is present is up to the operator and in many cases is an art, not a science. If the correlation is unsuccessful, the user has no way of reproducing the results (or lack thereof) later, and there is no way to put them in context in the entire environment; the results are essentially individual and independent. There are also modern intelligent leak locators such as the EASYSCAN system. Eliminating the need for manual distance

measurement: the operator automatically receives the GPS position of the two sensors, which can be manually adjusted via the device's street map (Figure 3).

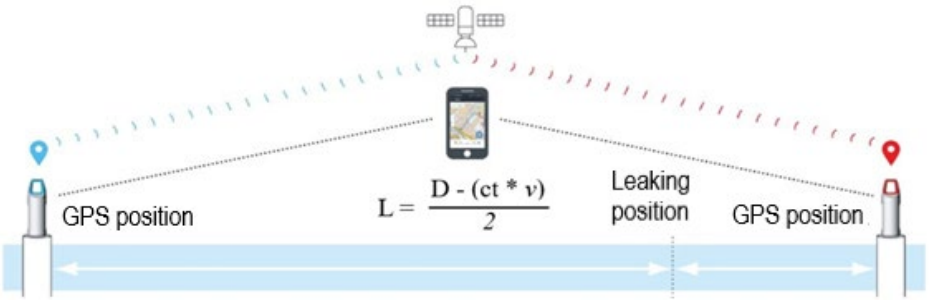


Fig. 3. *Illustration of leak location determination using the EASYSCAN system*

Any leaks detected will be automatically displayed at a precise geo-location on a street map. EASISCAN features an "auto filter" developed for high-quality Gutermann correlators. As soon as the sensors are programmed and positioned, the correlation result appears automatically, with no ambiguity in the results. At the end of the measurement, EASISCAN concludes whether or not a leak is present. If there is one, the operator activates the listening function by pressing a button and can listen to the noise of the leak at the indicated position. All measurements, whether there is a leak or not, can be recorded in the device's memory for later review [12]. After pinpointing the location of the leak with the help of the correlation function, acoustic listening is used to confirm the exact location above the earth's surface. Using GPS coordinates, the EASYSCAN application guides the operator to the expected location of the leak. The exact location can be seen on the street map. All information containing sound recordings can be saved on the map, and can be reviewed and listened to again later. The exact position is located with the help of GPS and displayed on the street map of the application. If a leak is found, it can be recorded on the map, along with the original search sound. The EASYSCAN application has an easy-to-understand and intuitive interface with which the entire leak detection process can be managed. It is connected to all sensors that are available by radio connection via the EASYSCAN link so that no additional cables are needed for connection. The application combines GPS and street map data, and thus enables an extensive overview of the locations and distances of all possible leak sites [12]. Measurements that are recorded can be saved for later review and playback. For advanced listening while working with a ground microphone, there are optional headphones that can be connected to a smartphone. Software uses automatic frequency filters to set the best parameters to get accurate results. Application works on all Android OS tablets and smartphones. Even in the heaviest road traffic, the correlation is performed successfully. Factors such as pipe depth, surface, soil type, different weather conditions cannot affect the correlation detection of leaks. Other devices used are acoustic loggers. They measure noise intensity over a period of time when looking for the lowest levels of noise or possible interference. Very low levels (measured values around 0) do not indicate a leak. In the case of leakage, the noise is constant and ideally it is the only noise that is measured. Loggers are usually mounted on surface equipment such as fire hydrants and can be permanently installed or used as needed for short periods of about two days.

PRESSURE CONTROL

A convenient method to reduce water losses due to leakage is to control pressure in the water supply network. It is a known fact that there is a direct relationship between pressure and water losses. Reducing the water pressure in the network reduces the amount of water escaping through any existing openings or leaks in the pipes. Measures to maintain pressure within optimal limits at low consumption are considered very effective and pay off quickly, as they also contribute to extending the life of pipes. This enables the pressure to be balanced

within the network, so that a larger number of customers can be served with very little increase in incoming water. A suitable method to reduce water losses due to leakage is A good solution is to use automatic pressure reducing valves and connecting equipment so that the pressure can be adjusted flexibly taking into account fluctuations such as e.g. change in inlet pressure, which can be further reduced at night when there is low consumption. In situations where underground pipelines have multiple leaks, pressure management can be among the most cost-effective methods of reducing losses, barring, of course, large leaks that require intervention. Siemens offers a solution that continuously monitors the value of the flow in different branches of the water supply network, which significantly reduces the time to detect leaks, the costs associated with this process, as well as water losses. The Siemens Siva LeakControl monitoring system is based on a three-step solution concept. During the first step, measures are taken to automatically detect leaks by continuously measuring the flow in defined parts of the network. The method is based on a complex monitoring system that measures flow using ultrasonic flow meters for non-invasive installation-Sitrans FST020. High accuracy and repeatability of measurements are of primary importance. The flow meter FST020 allows accurate measurement even at low speeds. Easy to assemble and disassemble, the converters have no contact with drinking water and can be installed in the ground even without a shaft. Data from the flow meter are transmitted to the central unit, where they are collected and estimated, and in case of suspected leakage, an alarm signal is generated. In the second step, the leak is located by temporarily placing additional acoustic sensors. The last step is to accurately determine the location of the leak using the correlator [13].

CONCLUSION

Water losses have socio-economic and environmental aspects. The fight against water scarcity and water resource management is increasingly relevant due to climate change. In addition to human needs, water is also needed to maintain natural ecosystems. Water prices are already causing tension in some regions, and water scarcity could lead to pressure to withdraw more water from natural ecosystems, some of which are already suffering from scarcity. Technological and digital innovations offer significant opportunities to improve water resource management. Implementation of digital twins, IoT technologies, automation and data analytics can significantly improve the monitoring, analysis and optimization of water supply systems. These approaches not only increase efficiency and reduce operational costs, but also help in the sustainable management of water resources in the future, ensuring their availability and quality for current and future generations. Integration of IoT devices and cloud technologies into the water monitoring system enables remote monitoring and data analysis at multiple locations, which contributes to efficient resource management and the prevention of water pollution. Artificial intelligence and machine learning offer opportunities to analyze big water monitoring data, identify patterns and predict potential risks to water quality. Advanced purification and monitoring methods are essential to ensure the safety and quality of drinking water. Technological innovations offer new opportunities to solve today's water supply challenges and enable access to clean and safe water for the population globally. Various software tools have been developed to determine the likelihood of leaks as well as possible sources, however, they all require the availability of some basic data about the water supply system, such as the amount of water supplied, billed and metered consumption, as well as the average operating pressure. Typically, such software solutions are not intended to and cannot replace performing a thorough due diligence, but they are a good way to start a leakage management program, as the software uses the input to calculate different types of actual and apparent losses as well as efficiency metrics. Losses of water distribution companies can be controlled by an annual audit of water supply activities and implementation of programs to identify and limit those that function poorly. Such programs include leakings management, water meter accuracy testing, and measures to combat water resources misuses. Commercial losses arise from inaccurate customer meters, billing system data inconsistencies, or unauthorized use. These losses cost the utility

revenue and distort data on customer consumption patterns. Losses are also physical, including water that leaves the water supply system due to leaks or overflows. To overcome the problem of large water losses, in addition to replacing aging piping and performing necessary repairs, other measures related to managing leaks in the system are also required. Leak management activities are associated with pressure control and leak location.

REFERENCES

[1] Stankov, S., Sistem nadzora i upravljanja postrojenjem za prečišćavanje vode, časopis Vodoprivreda, Beograd, broj 4-6, vol. 50, str. 319-332, 2018.
[2] Stankov, S., Water Purification in the Process Industry, Trideset sedmi međunarodni kongres o procesnoj industriji PROCESING 24, Beograd, 29-31 maj, Zbornik radova, DOI: 10.24094/ptk.024.121, str. 121-140, 2024.
[3] Stankov, S., Building management–modern tendencies, Annals of Faculty Engineering Hunedoara-International Journal of Engineering, ISSN: 1584-2665, vol. XXI, Fascicule 1, pp. 71-78, 2023.
[4] Stankov, P. S., Automation and Industry 4.0**,** journal Acta Technica Corviniensis – Bulletin of Engineering, ISSN: 2067-3809, Tome XIV, Fascicule 2, pp. 59-63, 2021.
[5] Stankov, P. S., Development of Automation in the Direction of Hyperautomation, Annals of Faculty Engineering Hunedoara–International Journal of Engineering, ISSN: 1584–2665, Publisher: University politehnica Timisoara, Faculty of engineering Hunedoara, Romania, Vol. XXI, fascicule 1, pp. 179–184, 2024.
[6] Stankov, S., Big Data in Water Supply and Sewerage System**,** journal Acta Technica Corviniensis-Bulletin of Engineering, ISSN: 2067-3809, Tome XV, Fascicule 1, pp. 21-25, 2022.
[7] Stankov, S., Merenje temperature pomoću PLC i SCADA sistema, časopis „Energetske tehnologije", Izdavač: Društvo za sunčevu energiju, Zrenjanin, vol. 7, br. 4, str. 13–22, 2010.
[8] Stankov, S., Upravljačko–nadzorni sistem pogona za proizvodnju biodizela, časopis Hemijska industrija, DOI: 10.2298/HEMIND180726024S, vol. 72, br. 6, str. 315-328, 2018.
[9] https://www.hitachi.com/businesses/infrastructure/product_site/water_environment/intelligent_water/index.html
[10] https://icpdas.blog/2022/06/30/icp-dass-solution-for-cloud-data-visualization-in-water-supply-monitoring-system-india/
[11] https://www.minal.rs/pdf/Stethophon%2004_srb_web.pdf
[12] https://en.gutermann-water.com/products/leak-noise-correlators/
[13] https://cache.industry.siemens.com/dl/files/075/104423075/att_112125/v1/FST020_IP65_NEMA_4x_OI_EN_en-US.pdf

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SOLAR ENERGY IN THE REPUBLIC OF SERBIA: THE POTENTIAL AND LEGAL FRAMEWORK

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Abstract: This paper analyzes the potential of solar energy, the existing legal framework, and the state of installed capacities in the Republic of Serbia, in order to determine, through comparison with the European Union (EU) average, the degree of development and to identify opportunities for improving legislation. Solar energy is one of the fastest-growing renewable energy sources (RES) and a key element in achieving the European Union's climate neutrality goals. The study reviews the evolution of EU legislation, from RED I to RED III, together with the REPowerEU plan and the EU Solar Energy Strategy (2022). Serbia's solar potential exceeds the European average by approximately 30%, yet its utilization remains limited. The Law on the Use of Renewable Energy Sources (LURES) has largely transposed the RED II Directive, introducing measures such as the buyer–producer model, guarantees of origin, and market-based incentives. However, delays in adopting by-laws and incomplete harmonization with EU legislation hinder full implementation. The findings support the hypothesis that, despite favorable natural conditions and the existence of a partially harmonized legal framework, the share of solar energy in Serbia's total renewable energy capacity significantly lags behind the EU average, indicating the need for more intensive development of this sector and further alignment with EU legislation.
Key words: solar energy potential, legal framework

INTRODUCTION

Energy is one of the most important resources on our planet and is of limited availability, facing increasing global demand and sustainability challenges [1,2]. Due to rapid population growth, modern lifestyle, and technological advancement, the world's energy demand is expected to rise significantly in the coming decades [3]. According to United Nations (UN) projections, the world population will increase from an estimated 8.5 billion in 2030 to 9.7 billion in 2050 [4], which will require a substantial expansion of energy production to meet growing needs. The energy sector represents a key component of sustainable development [5], while ensuring sufficient access to clean and affordable energy sources is one of the fundamental commitments of contemporary policy [6]. Fluctuations in fossil fuel prices, climate change, and the instability of global energy markets have highlighted the need to accelerate the transition toward renewable energy sources (RES) [7]. Among them, solar energy stands out as one of the fastest-growing and most accessible forms of renewable energy, both within the European Union (EU) and globally [8,9]. It is affordable, clean, and plays a central role in the green transition toward climate neutrality. According to the International Renewable Energy Agency (IRENA), by the end of 2021 global solar capacity had reached 843 GW (gigawatts), representing a 19% increase compared to the previous year [7]. Based on IRENA data, this capacity more than doubled compared to 2017 levels. Furthermore, international reports emphasize that additional acceleration in the development of RES, and particularly solar energy, is necessary to achieve the targets of the Paris Agreement [6] [7]. Solar energy represents one of the most promising renewable energy sources, both globally and within the energy sector of the Republic of Serbia. Although the Republic of Serbia possesses significant solar potential and a legislative framework largely aligned with European standards, there are considerable differences in the level of utilization of this resource compared to the EU [10]. The aim of this paper is to analyze the potential of solar energy in the Republic of Serbia, the existing legal framework, and the state of installed capacities, and to determine, through

comparison with the EU average, the degree of development and to identify opportunities for improving legislation. The hypothesis of this research is that, despite favorable natural conditions and the existence of a harmonized legal framework, the share of solar energy in the total renewable energy capacity of the Republic of Serbia still significantly lags behind the EU average, indicating the need for more intensive development of this sector and for further harmonization of national with EU legislation. Although a harmonized and adequate legal framework is an important prerequisite, it represents only one of the elements necessary for the further development of this renewable energy source in Republic of Serbia.
The methodology encompasses an analysis of the domestic and EU legal framework, a review of relevant literature, and a comparative approach.

THE POTENTIAL OF SOLAR ENERGY IN THE REPUBLIC OF SERBIA

Solar photovoltaic (PV) energy is a widely available, environmentally friendly, and economically viable alternative to conventional energy sources [11]. According to the International Renewable Energy Agency (IRENA), in only 71 minutes the Earth receives enough solar energy to meet humanity's annual energy demand [12]. The Republic of Serbia possesses excellent potential for solar energy utilization [13]. Solar power accounts for approximately 16.7% of the country's technically usable renewable energy potential, while the energy potential of solar radiation is about 30% higher than in Central Europe, with radiation intensity among the highest in Europe [14]. Nevertheless, the utilization of solar energy in Republic of Serbia remains in its early stages [15]. According to Lambić [14], the average daily global solar radiation for a flat surface in Republic of Serbia during winter ranges from 1.1 kWh/m² in the north to 1.7 kWh/m² in the south, while during summer it ranges from 5.4 kWh/m² in the north to 6.9 kWh/m² in the south. For comparison, the average annual value in Germany is around 1,000 kWh/m², whereas in Serbia it is approximately 1,400 kWh/m². Stamenić [16] further noted that the most favorable areas in the Republic of Serbia record a high number of sunshine hours, with the annual ratio of actual irradiance to total possible irradiance being approximately 50%. According to Lambić [14], most of the Republic of Serbia records between 1,500 and 2,200 sunshine hours annually, with an average annual solar irradiation ranging from 1,200 to 1,550 kWh/m². The most favorable areas include Vojvodina and southeastern Serbia, where the potential for PV conversion is particularly high. Stamenić [16] further emphasized that, with the technology available at the time, PV conversion efficiencies between 14% and 20% were achievable, indicating significant opportunities for expanding solar installations in the country. Although the Republic of Serbia has real potential for the production and application of solar energy, these potentials are still not sufficiently utilized, despite the existence of a harmonized legal framework [13]. In order to assess the position of the Republic of Serbia in relation to the EU, a comparison of installed renewable energy capacities was carried out based on Eurostat data for 2024 [17].

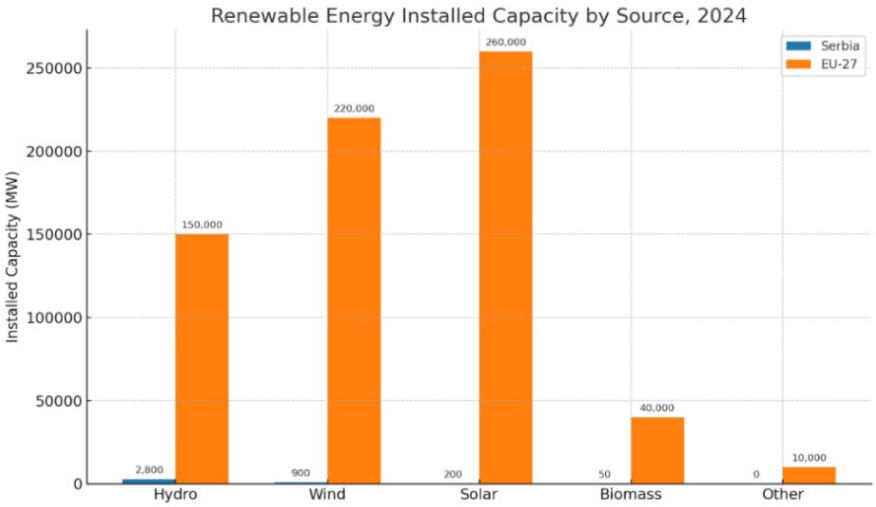


Fig. 1. *Installed renewable energy capacity by source in 2024: comparison between the Republic of Serbia and the EU.*

According to Eurostat [17], Serbia has a dominant share of hydropower within its total renewable energy capacities, while solar energy accounts for only a small fraction. The comparative chart of Serbia and the EU-27 clearly shows that the share of solar power plants in Serbia is several times smaller than in the EU. This outcome supports the initial hypothesis of underdeveloped solar energy deployment in Serbia, despite the existence of a harmonized legal framework.

LEGAL FRAMEWORK IN THE EUROPEAN UNION

The European Union (EU) has developed a comprehensive legal framework for RES, including solar energy, aimed at achieving climate neutrality and ensuring energy security. This framework has evolved significantly over the past fifteen years, reflecting both the EU's environmental commitments and the need to reduce dependence on fossil fuels. In the EU, solar energy has significant potential to rapidly become an indispensable part of the EU electricity and heating system and a major driver for achieving the European Green Deal objectives, while gradually eliminating the EU's dependence on Russian fossil fuels. By the end of 2020, the EU had reached 136 GW of installed photovoltaic (PV) capacity, with more than 18 GW added in that year alone. PV systems accounted for around 5% of total EU electricity generation [18]. To meet the 2030 renewable energy target proposed by the European Commission and the objectives of the REPowerEU plan, the deployment of solar energy must be significantly accelerated, requiring the installation of approximately 45 GW per year during this decade [10]. In the last decade and a half, the EU has gradually strengthened its legislation in the field of RES, adapting it to more ambitious climate and energy objectives. As a complement to the Renewable Energy Directives (RED I–III), the massive and rapid deployment of RES is central to the REPowerEU plan and the EU Solar Energy Strategy, which position solar energy as a simple and abundant resource and a key driver for reducing the EU's reliance on fossil fuels across all economic sectors [10]. In 2019, the regulatory framework known as the Clean Energy for All Europeans package was adopted, comprising eight legislative acts in the field of climate and energy. Among these are Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources, which sets renewable energy targets for 2030 [19], and Regulation (EU) 2018/1999 on the Governance of the Energy Union and Climate Action, which, among other provisions, requires that future measures and targets in the field of RES be included in the Integrated National Energy and Climate Plans (NECP) [20].

The principal legislative framework in this field is the Renewable Energy Directive (RED). Directive 2009/28/EC, adopted in 2009, established a binding target of a 20% share of energy

from RES in gross final energy consumption by 2020 [21]. This was subsequently updated by Directive (EU) 2018/2001 (RED II), which set a target of at least 32% by 2030 and required transposition into national law by 30 June 2021 [19]. Following the adoption of the European Green Deal [8], the EU adopted more ambitious climate objectives through the European Climate Law, which establishes a binding target of a net domestic reduction of greenhouse gas (GHG) emissions of at least 55% by 2030 compared to 1990 levels, and climate neutrality by 2050 [22]. Further revisions were proposed under the Fit for 55 package in July 2021, where increasing the share of renewable energy, particularly solar, was identified as a key measure to achieve these goals. The revised Renewable Energy Directive (RED III) establishes that the share of renewable energy in the Union's gross final consumption shall be at least 42.5% by 2030, with a collective aim to reach 45% [23]. RED III forms part of the Fit for 55 legislative package, which seeks to ensure that the Union reduces its net GHG emissions by at least 55% by the end of the decade.

LEGAL FRAMEWORK IN THE REPUBLIC OF SERBIA

Following the entry into force of the Stabilisation and Association Agreement (SAA) on 1 September 2013 [24], the Republic of Serbia obtained the status of an EU-associated country. By adopting the Law on the Ratification of the Treaty on the Establishment of the Energy Community [25], Serbia became a member of the Energy Community and undertook the obligation to implement European directives in the field of RES. With the adoption of the Law on the Use of Renewable Energy Sources (LURES),[26] most provisions of Directive (EU) 2018/2001 – RED II were "for the most part transferred" into the Serbian legal system (Government of the Republic of Serbia, 2021). As a lex specialis in the field of RES, LURES introduced a number of key innovations aimed at stimulating investment and aligning national legislation with the EU's decarbonization commitments. Among the most important innovations are new incentive mechanisms for RES-based electricity generation and provisions defining the balancing responsibility of guaranteed suppliers, in line with the EU Guidelines on State Aid for Environmental Protection. One of the most significant novelties introduced by LURES was the expansion of the prosumer concept, allowing final consumers to install their own RES facilities under simplified procedures and offset their consumption through net metering or net billing (Arts. 51–54 LURES). Another novelty was the possibility of directly concluding commercial power purchase agreements (PPAs) between RES producers and buyers (Art. 46 LURES). Studies show that the introduction of prosumers and PPAs increases market competitiveness and accelerates the integration of distributed RES generation [27]. Despite these reforms, certain regulatory gaps remained. The feed-in tariff framework was incomplete, as no model contracts or quotas were adopted, and the three-year incentive plan required by law was not implemented (Art. 14 LURES). This regulatory uncertainty discouraged investors and contributed to delays in project realization, confirming findings from comparative studies that incomplete support schemes reduce investment security and long-term RES development [28]. The market premium system, although market-oriented, required a liquid electricity market. According to the USEA study on large-scale RES integration in Serbia (2022) [29], linking the Serbian power exchange (SEEPEX) with neighboring EU markets would significantly improve liquidity and facilitate RES integration. Furthermore, studies analyzing SEEPEX and European market coupling indicate that connecting SEEPEX with day-ahead and intraday EU markets can enhance price stability, liquidity, and long-term RES integration [30][31]. Persistent delays in adopting by-laws created overlaps and inconsistencies with the Law on Energy (LE), underscoring the need for urgent regulatory harmonization. Another key innovation of LURES was the introduction of a regulated system of guarantees of origin (Arts. 49–51 LURES). A guarantee of origin (GO) is an electronic document certifying that a specific quantity of electricity has been produced from RES, in line with Article 19 of Directive (EU) 2018/2001 (RED II). In Serbia, guarantees of origin are issued by the transmission system operator (EMS), and they can be transferred,

traded, or canceled once the corresponding electricity is consumed. However, the Serbian GO system is not yet fully integrated with the European Energy Certificate System (EECS), coordinated by the Association of Issuing Bodies (AIB). Without international recognition, the tradability of Serbian GOs is limited, which reduces investment security and weakens the competitiveness of RES projects [32]. Although LURES set a six-month deadline for the adoption of all relevant by-laws, this deadline was not fully met, which led to inconsistencies with the Law on Energy (LE). Amendments to the LE were adopted in 2021 to resolve part of these issues, particularly concerning incentive mechanisms and balancing responsibility. [33] Serbia continues to harmonize its energy sector regulations with the EU acquis, and further amendments to the LE were adopted at the end of 2024 [34], introducing certification for RES system installers, new conditions for issuing energy permits in line with strategic documents, the concept of active customers and aggregators, as well as changes to the methodology for determining electricity prices for guaranteed supply. The results of the analysis show that the Republic of Serbia has a dominant share of hydropower in its total renewable energy capacity, while solar energy accounts for only a minor share. A comparison with the EU average clearly reveals that the share of solar power plants in Serbia is several times lower, which confirms the initial hypothesis of underdeveloped deployment in this sector.
Although the legislative framework in the field of renewable energy is largely harmonized with European directives and represents a key incentive for development, the achieved capacities demonstrate that normative harmonization alone is not sufficient. It is necessary to ensure additional investments, develop market mechanisms, while transparent regulation and integration into European energy markets remain essential to unlock Serbia's solar potential and enable convergence with the European average.

CONCLUSION

Solar energy plays a key role in the global transition to clean energy and in achieving net-zero emissions. It is cost-effective, clean, and adaptable, making it the fastest-growing source of energy in the EU. In this context, the REPowerEU plan, adopted and revised in 2023, aims to reduce the EU's dependence on Russian fossil fuels. As part of this plan, the European Commission presented the EU Solar Energy Strategy (2022), a comprehensive roadmap for the accelerated deployment of solar capacity. The fundamental legislative act in this field is Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources (RED II), which has since undergone three revisions. In the Republic of Serbia, the LURES is designed to support a significant increase in the capacity of facilities generating electricity from RES. The law includes numerous innovations aimed at aligning national legislation with the EU acquis while taking market realities into account. Although the law has largely transposed the RED II Directive, the provisions of the most recent RED III Directive have not yet been implemented. Key reforms include the buyer–producer model, the issuance of guarantees of origin (GO), the prosumer schemes (net metering and net billing), the possibility of concluding commercial power purchase agreements (PPAs), and the shift to market-based incentive schemes such as the market premium. A necessary step also highlighted in recent studies is the integration of the Serbian electricity exchange (SEEPEX) with EU markets in order to improve liquidity and facilitate long-term RES integration. The 2024 Amendments to the Law on Energy further introduced certification of RES system installers, active customers and aggregators, as well as new conditions for issuing energy permits. Serbia's solar potential, which exceeds the European average, combined with a progressively developing legal framework, provides a strong foundation for accelerating solar energy deployment. To fully realize this potential, strategic priorities should include completing regulatory harmonization, establishing stable and transparent investment conditions, and enabling integration into the European electricity market. The findings of this research confirm the initial hypothesis: despite favorable natural conditions and the existence of a harmonized legal framework, the share of solar energy in Serbia's total RES capacity significantly lags behind the EU average.

Therefore, additional investments, the development of market mechanisms (such as commercial PPA contracts), and the accelerated implementation of secondary legislation are necessary for Serbia's solar potential to be realized at a level that would bring the country closer to the European average.

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REFERENCES

[1] Carmona-Moreno, C., Crestaz, E., Cimmarrusti, Y., Farinosi, F., Biedler, M., Amani, A., Mishra, A., & Carmona-Gutierrez, A. (2021). *Implementing the Water–Energy–Food–Ecosystems Nexus and Achieving the Sustainable Development Goals.* UNESCO, European Union, IWA Publishing.

[2] Acosta-Silva, Y., Torres-Pacheco, I., Matsumoto, Y., Toledano-Ayala, M., Soto-Zarazúa, G., Zelaya-Ángel, O., & Méndez-López, A. (2019). Applications of solar and wind renewable energy in agriculture: A review. *Science Progress, 102*(2), 127–140. https://doi.org/10.1177/0036850419838011

[3] Iheanetu, K. J. (2022). Solar photovoltaic power forecasting: A review. *Sustainability, 14*(24), 17005. https://doi.org/10.3390/su142417005

[4] United Nations, Department of Economic and Social Affairs, Population Division. (2022). *World Population Prospects 2022: Summary of Results.*

[5] Alose, D., & Mlambo, G. (2023). Integration of technology in education and its impact on learning and teaching.

[6] United Nations. (2015). *Transforming our world: The 2030 Agenda for Sustainable Development.* United Nations, New York.

[7] International Renewable Energy Agency (IRENA). (2022). *Renewable Capacity Statistics 2022.* IRENA, Abu Dhabi.

[8] European Commission. (2019). *Communication from the Commission: The European Green Deal.* COM(2019) 640 final, Brussels, 11 December 2019.

[9] SolarPower Europe. (2022). *Global Market Outlook for Solar Power 2022–2026.* SolarPower Europe, Brussels.

[10] European Commission. (2022). *An EU Solar Energy Strategy for 2030 and beyond.* Communication COM (2022) 221 final (part of REPowerEU).

[11] Sass, J., & Hahn, H. (2020). *Solar powered irrigation systems (SPIS): Technology, economy, impacts.* Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.

[12] International Renewable Energy Agency (IRENA). (2020). *Renewable power generation costs in 2020.* Abu Dhabi: IRENA.

[13] Ljubojev, N., Dukić Mijatović, M., & Pekez, J. (2024). Solar energy as a driver of sustainable development in agriculture: Potential and legal framework for implementation in the Republic of Serbia. *Economics of Agriculture, 71*(3), 1051–1070. https://doi.org/10.59267/ekoPolj24031051L

[14] Lambić, M. (Ed.). (2011). *Studija o proceni ukupnog solarnog potencijala – solarni atlas i mogućnosti proizvodnje i korišćenja solarne energije na teritoriji AP Vojvodine.* Novi Sad: Pokrajinski sekretarijat za energetiku i mineralne sirovine.

[15] Jakovljević, T. (2022). *111 Questions and answers about solar energy.* Center for Environmental Improvement.

[16] Stamenić, Lj. (2009). *Use of solar photovoltaic energy in Serbia.* Jefferson Institute.

[17] Eurostat. (2024). *Renewable energy statistics.* Eurostat Statistics Explained.

[18] Eurostat. (2021). *Electricity production, consumption and market overview.* Eurostat Statistics Explained.

[19] Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (RED II). *Official Journal of the European Union,* L 328/82, 21.12.2018. CELEX: 32018L2001.

[20] Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action. *Official Journal of the European Union,* L 328/1, 21.12.2018. CELEX: 32018R1999.

[21] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources. *Official Journal of the European Union,* L 140/16, 5.6.2009. CELEX: 32009L0028.

[22] Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality (European Climate Law). *Official Journal of the European Union,* L 243/1, 9.7.2021. CELEX: 32021R1119.

[23] Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 on the promotion of the use of energy from renewable sources, amending and subsequently repealing Directive (EU) 2018/2001 (RED III). *Official Journal of the European Union,* L 2023/2413, 31.10.2023. CELEX: 32023L2413.

[24] Stabilisation and Association Agreement, *Official Journal of the EU,* L 278, 18.10.2013.

[25] Law on the Ratification of the Treaty on the Establishment of the Energy Community (Zakon o ratifikaciji Ugovora o osnivanju Energetske zajednice), Official Gazette of RS – International Treaties, No. 62/2006

[26] Law on the Use of Renewable Energy Sources (Zakon o korišćenju obnovljivih izvora energije), *Official Gazette of RS*, No. 40/2021.

[27] European Commission. (2021). *Study on energy communities and prosumers in the EU energy market.* Brussels: European Commission.

[28] Kitzing, L., Mitchell, C., & Morthorst, P.E. (2012). Renewable energy policies in Europe: Converging or diverging? *Energy Policy, 51,* 192–201. https://doi.org/10.1016/j.enpol.2012.08.064

[29] USEA. (2022). *RES Integration in Serbia and Recommendations for Action.* United States Energy Association.

[30] Božić, Z., Dobromirov, D., Arsić, J., Radišić, M., & Słusarczyk, B. (2020). Power exchange prices: Comparison of volatility in European markets. *Energies, 13*(21), 5620. https://doi.org/10.3390/en13215620

[31] Terzić, I., Jeremić, Z., & Latas, T. (2023). Modelling and forecasting volatility on Electric Power Exchange SEEPEX. *Management, 28*(2), 67–78. https://doi.org/10.7595/management.fon.2021.0002

[32] Terzić, I., & Jeremić, Z. (2022). Guarantees of origin and renewable energy market integration in Southeast Europe. *Journal of Energy Law and Policy, 15*(2), 87–102.

[33] Law on Amendments to the Energy Law (Zakon o izmenama i dopunama Zakona o energetici), *Official Gazette of RS*, No. 145/2021.

[34] Law on Amendments to the Energy Law (Zakon o izmenama i dopunama Zakona o energetici), *Official Gazette of RS,* No. 92/2024.

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COMPARATIVE ANALYSIS OF RESIDENTIAL PHOTOVOLTAIC SYSTEMS: IMPACT OF SHADING AND ORIENTATION ON ENERGY PRODUCTION

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Abstract: Residential photovoltaic (PV) systems represent a growing trend in sustainable energy generation. Their efficiency is significantly influenced by installation parameters such as orientation, tilt angle, and shading. This paper conducts a comparative study of two PV systems under similar residential conditions: one with an optimal south-facing orientation, and a second that is partially shaded and primarily west-facing. The energy production of both systems is analyzed over a representative period. This analysis reveals the production losses attributed to shading and suboptimal orientation. Results demonstrate significant disparities in energy yield and efficiency, which underscores the necessity of proper system design for achieving long-term financial viability and energy independence. The findings of this study provide a better understanding of the practical challenges encountered in residential PV deployment, informing decisions related to system sizing and placement.
Key words: PV, grid, photovoltaic systems, energy efficiency, residential applications, shading losses, panel orientation

INTRODUCTION

The global transition towards renewable energy sources has placed photovoltaic (PV) systems at the forefront of sustainable energy generation. In particular, residential PV installations have gained significant attention due to their ability to provide clean energy, reduce household electricity costs, and contribute to decarbonization targets. Within the European context, initiatives such as the European Green Deal emphasize the strategic role of solar energy in achieving climate neutrality by 2050. Similar policies and incentives worldwide continue to drive the adoption of residential PV systems as an accessible and effective solution for both individual households and the broader energy grid [1], [2].

Despite these advantages, the performance of PV systems is highly dependent on environmental and installation-related factors. Among the most critical parameters influencing energy yield are the orientation, tilt angle, and the presence of shading. While optimally oriented PV systems can operate close to their rated efficiency, residential installations often face limitations such as roof geometry, architectural constraints, or surrounding obstacles (trees, neighboring buildings), which result in suboptimal placement. These conditions can lead to reduced energy production, mismatch losses, and lower overall efficiency, undermining the financial and environmental benefits of the system [3], [4].

The aim of this paper is to provide a comparative analysis of two residential PV systems installed under different conditions: one with optimal orientation towards the south and minimal shading, and another partially shaded and oriented towards the west. By examining the energy production of both systems over a defined period, the study highlights the quantitative impact of shading and misalignment on electricity generation. The results emphasize the importance of proper design and installation in residential applications, offering practical insights for homeowners, installers, and policymakers. Furthermore, the findings underline the necessity of considering advanced technologies such as micro-inverters and power optimizers to mitigate shading effects and improve system performance [5], [6].

METHODOLOGY

Description of the Analyzed Systems

For this study, two residential photovoltaic (PV) systems installed under different conditions were selected in order to evaluate the impact of orientation and shading on energy production. Both systems are located in the same geographical region to ensure comparable climatic conditions, but differ in installation geometry and exposure to shading.

- System 1 (Optimally Oriented): Installed with a south-facing orientation and a tilt angle close to the site's latitude, ensuring maximum annual irradiance capture. This system has minimal shading throughout the day.
- System 2 (Shaded and West-Facing): Installed with a west-facing orientation, with modules receiving direct sunlight predominantly in the afternoon. The system is partially affected by shading from nearby obstacles, leading to significant mismatch losses.

Both systems utilize monocrystalline silicon PV modules of same nominal 5.2 KW capacity to allow for direct comparison. The installed power, number of modules, and inverter specifications are the same [7].

Site Location and Climatic Conditions

The analyzed residential photovoltaic installations are situated in Socodor, Arad, Romania, a region characterized by a temperate-continental climate. The average annual solar irradiation based on Global Solar Atlas (World Bank/ESMAP, Solargis) is approximately 1,300 kWh/m², which provides favorable conditions for solar energy generation. Climatic data, including solar irradiance and ambient temperature, were obtained from the nearest meteorological station to validate the environmental parameters during the monitoring period. Since all installations are located within the same geographical area, the influence of environmental variability is minimized, ensuring that observed performance differences can be primarily attributed to panel orientation and shading effects rather than climatic disparities [8].

Equipment Specifications

PV Modules: Both systems are equipped with 12 monocrystalline PV panels rated at 425 W/module, chosen for their high efficiency and suitability in residential applications.
Inverters: Each system employs a grid-connected inverter, with maximum efficiency above 97%. The inverter for System 1 is equipped with dual MPPT trackers, while System 2 utilizes a similar inverter but without optimizers.
Mounting Structures: Aluminum-based mounting frames adapted to the roof geometry of each residence [9].

Data Acquisition and Monitoring

Energy production data were collected over a period of one month (September 2024), using integrated inverter monitoring platforms and a smart meter installed at each site. The monitored parameters include: Daily energy yield (kWh), Power injected into the grid (kWh), Self-consumption from PV (kWh), Energy imported from the grid (kWh).
This approach provides sufficient temporal resolution for comparative analysis of orientation/shading impacts while relying on well-established PV monitoring practices. Data treatment considered known behaviors of PV arrays under partial shading (multiple MPPs, power oscillations) and temperature-dependent performance, as reported in modelling and diagnostic studies [10], [11], [12], [13]. The chosen indicators are standard for residential PV performance assessment and fault/underperformance screening [4], [13].

RESULTS AND DISCUSSION

Energy Yield Comparison

The monitored data show a significant difference in the energy production between the optimally oriented PV system (System 1) and the west-facing, partially shaded system (System 2). Table 1 summarizes the daily yields for a representative 10-day period in September.

Table 1. *Comparative daily yields for the two PV systems (4-15 July 2025)*

Day	Date	System 1 – South-facing (kWh)	System 2 – West-facing & shaded (kWh)	Difference (%)
1	4 July 2025	34.05	22.53	-33.83%
2	5 July 2025	35.12	24.72	-29.61%
3	6 July 2025	33.02	22.57	-31.65%
4	7 July 2025	29.03	15.48	-46.68%
5	8 July 2025	22.71	10.54	-53.59%
6	9 July 2025	7.21	5.42	-24.83%
7	10 July 2025	16.33	13.11	-19.72%
8	11 July 2025	18.56	13.27	-28.50%
9	12 July 2025	24.81	16.18	-34.78%
10	13 July 2025	28.78	20.36	-29.26%

The results indicate that System 2 consistently produced 30–35% less energy than System 1, with losses difference being less pronounced on partially cloudy days (Days 6–8), when shading affected also the well faced system making it to work closer to a shaded system.

Economic Implications

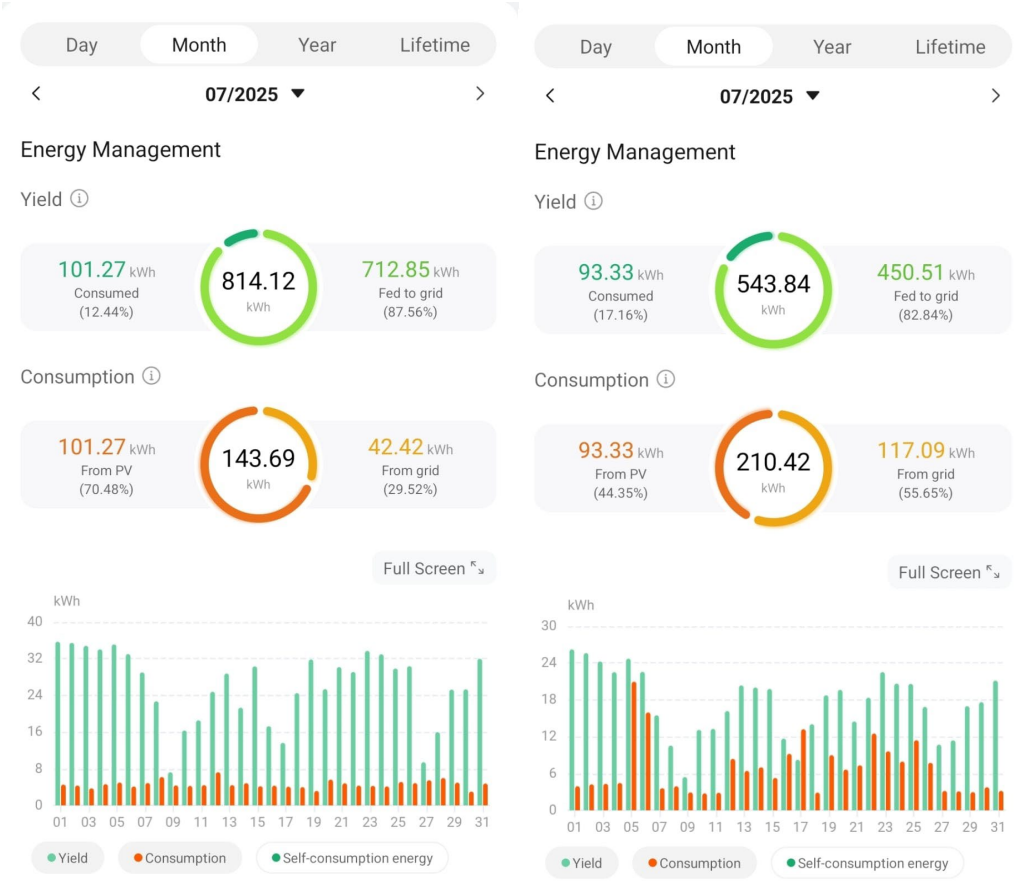


Fig. 1. *System 1 (on left) and System 2 (on right) production and consumption in July 2025*

Based on Fig. 1 and assuming an average residential electricity price of 0.20 €/kWh, the monthly savings from System 1 were approximately €163 in July, compared to only €109 for System 2 in July, which directly impacts the payback period of the investment.
While both systems reduce household electricity bills, the optimally oriented installation provides a significantly higher return on investment [14]. Homeowners with shaded or misaligned systems may need to consider additional solutions, such as micro-inverters or optimisers, to mitigate shading losses [15].

Discussion

The results demonstrate that suboptimal installation conditions can reduce PV energy yield by up to one third, even when identical module technologies and inverters are used. While west-facing systems may still provide valuable afternoon peak generation, shading exacerbates losses and increases system mismatch [16]. For residential applications, careful assessment of roof geometry and shading obstacles is essential to maximize system performance.
Advanced solutions such as power optimizers, micro-inverters, or bifacial modules may partially compensate for shading and orientation issues, though they increase upfront costs. Ultimately, the findings highlight the necessity of proper system design in residential contexts to ensure both economic viability and long-term sustainability [17].

CONCLUSION

This study analyzed the performance of two residential photovoltaic (PV) systems installed under different conditions: one south-facing with optimal orientation, and another west-facing and partially shaded. The comparative analysis highlighted a consistent reduction in energy yield of approximately 30%-35% for the shaded and misaligned system.
The results demonstrate that orientation and shading are critical factors influencing PV system efficiency, with direct consequences on both energy yield and financial viability. While both systems contributed to household energy savings, the optimally oriented installation provided significantly higher production, resulting in shorter payback times and improved long-term benefits. From a practical perspective, the findings emphasize the importance of site assessment prior to installation. Homeowners and installers should carefully evaluate shading obstacles and roof geometry to maximize performance. In cases where optimal orientation is not possible, mitigation strategies such as power optimizers, micro-inverters, or advanced module technologies should be considered.
In conclusion, proper design and installation remain essential to unlocking the full potential of residential PV systems. By minimizing shading effects and ensuring optimal orientation, households can achieve higher efficiency, greater energy independence, and enhanced sustainability, contributing to broader renewable energy integration targets.

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REFERENCES

[1] International Energy Agency (IEA), *Renewables 2023 – Analysis and forecast to 2028*. Paris: IEA, 2023. [Online]. Available: https://www.iea.org/reports/renewables-2023

[2] Petcuț-Lasc, A.-A., Bălaș, V. E., & Petcuț, F. M., "Analysis of a residential photovoltaic system," in *Proceedings of the XIV International Conference on Industrial Engineering and Environmental Protection (IIZS 2024)*, Zrenjanin, Serbia, pp. 198–205, 2024.
[3] Fraunhofer Institute for Solar Energy Systems ISE, *Photovoltaics Report*. Freiburg, Germany, 2024. [Online]. Available: https://www.ise.fraunhofer.de
[4] Petcuț-Lasc, A.-A., Bălaș, V. E., Petcuț, F. M., Rotar, R., & Alexuță, D., "Performance evaluation of a residential photovoltaic system in Matlab Simulink," in *2025 IEEE 23rd World Symposium on Applied Machine Intelligence and Informatics (SAMI)*, pp. 435–440, 2025.
[5] Fesharaki, V. J., Dehghan, M., Fesharaki, J. J., and Tavasoli, H., "The effect of tilt angle, orientation and shadow on the amount of solar radiation received by a photovoltaic panel," *Renew. Sustain. Energy Rev.*, vol. 15, no. 9, pp. 502–506, Dec. 2011.
[6] Petcuț-Lasc, A.-A., Bălaș, V. E., & Petcuț, F. M., "A survey of MPPT techniques under partial shading conditions: Evaluating the Firefly algorithm's performance," in *2025 18th International Conference on Engineering of Modern Electric Systems (EMES)*, pp. 1–6, 2025.
[7] Duffie, J. A., and Beckman, W. A., *Solar Energy: Fundamentals, Design, Modelling and Applications*. Hoboken, NJ: Wiley, 2020.
[8] Solargis, "Global Solar Atlas," World Bank Group/ESMAP, 2023. [Online]. Available: https://globalsolaratlas.info
[9] Luque, A., and Hegedus, S., *Handbook of Photovoltaic Science and Engineering*, 2nd ed. Hoboken, NJ: Wiley, 2011.
[10] Chouder, A., Silvestre, S., Sadaoui, N., and Rahmani, L., "Modeling and simulation of a grid connected PV system based on the evaluation of main PV module parameters," *Simulation Modelling Practice and Theory*, vol. 20, no. 1, pp. 46–58, Jan. 2012.
[11] Gow, J. A., and Manning, C. D., "Development of a photovoltaic array model for use in power electronics simulation studies," *IEE Proc. – Electr. Power Appl.*, vol. 146, no. 2, pp. 193–200, Mar. 1999.
[12] Patel, H., and Agarwal, V., "MATLAB-based modeling to study the effects of partial shading on PV array characteristics," *IEEE Trans. Energy Convers.*, vol. 23, no. 1, pp. 302–310, Mar. 2008.
[13] Silvestre, S., Chouder, A., and Karatepe, E., "Automatic fault detection in grid connected PV systems," *Sol. Energy*, vol. 94, pp. 119–127, Aug. 2013.
[14] Byrne, J., Zhou, A., Shen, B., and Hughes, K., "Evaluating the economics of photovoltaic systems: Shading, orientation and location effects," *Renew. Sustain. Energy Rev.*, vol. 75, pp. 1008–1019, Aug. 2017.
[15] Deline, C., Marion, B., Granata, J., and Gonzalez, S., "A performance and economic analysis of distributed power electronics in photovoltaic systems," *NREL Tech. Rep. NREL/TP-5200-50003*, 2011.
[16] Quaschning, V., and Hanitsch, R., "Influence of shading on electrical parameters of solar cells," *Sol. Energy*, vol. 56, no. 6, pp. 513–520, Jun. 1996.
[17] Massi Pavan, A., Mellit, D., and Diallo, D. A., "Advanced photovoltaic systems with bifacial modules: Performance, challenges, and opportunities," *Renew. Energy*, vol. 169, pp. 92–109, May 2021.



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Designing and Maintenance

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HB9CV ANTENNA: THEORETICAL AND PRACTICAL ASPECTS

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Abstract: Due to its excellent electromagnetic and electrical characteristics, compactness, and ease of manufacturing, the HB9CV is one of the most popular antennas among radio amateurs. In its simplest form, the HB9CV consists of two unequal length dipoles that are fed by phasing lines. This makes both dipoles active elements. By using two active elements in the HB9CV antenna, instead of one as in the Yagi antenna, a higher gain is achieved for the same physical dimensions of the antenna. Since the first introduction of the HB9CV antenna until today, radio amateurs have developed numerous versions of the HB9CV antenna. Most versions of HB9CV antennas use additional parasitic elements for the reflector and directors. In this paper, a review of the HB9CV antenna family is given. The electromagnetic characteristics of HB9CV antennas with two elements and with four elements (two active and two parasitic elements) were analyzed using 4NEC2 software and presented in detail. The four-element version of the HB9CV antenna was assembled. The electrical parameters of the assembled antenna were measured with a vector analyzer and presented.
Key words: antenna, directional antenna, HB9CV antenna, radio amateurs

INTRODUCTION

The popularity and widespread use of a particular type of antenna among radio amateurs depends on several factors. The antenna must have good electromagnetic and electrical characteristics and should be relatively simple to assemble [1, 2]. Since the dimensions of the antenna are proportional to the operating wavelength, today radio amateurs prefer to work on very high frequency (VHF) and ultra high frequency (UHF) because the antennas are significantly smaller in VHF and UHF compared to the once popular high frequency (HF) [1-4]. Also, the antenna must have sufficient mechanical durability to withstand wind blows if it is stationary and accidental impacts if it is a portable antenna [5], or the antenna is used in confined spaces [6] and stressful situations [7]. Also, radio amateurs rarely own expensive tools for working with metal, wood and plastic, nor do they have much experience in working with them. For this reason, radio amateurs prefer antennas that do not require expensive and specialized tools. Radio amateurs also prefer that the tools used in making antennas do not require much experience in their use.
Several types of antennas satisfy the above. Among the most famous are: dipole antenna, ground plane antenna, Yagi antenna family, Quad antenna family and HB9CV antenna family [1-4]. This paper will describe in detail directional antenna called HB9CV [1-4]. HB9CV antennas are typically used on very high frequencies (VHF) and ultra high frequencies (UHF) and are also popular as portable direction-finding devices. In this paper, a review of the HB9CV antenna family is given. The electromagnetic characteristics of HB9CV antennas with two active elements and with four elements (two active and two parasitic elements) were analyzed using 4NEC2 software [8] and presented in detail. The selected operating frequency for both antennas is 446 MHz (also known as professional mobile radio or private mobile radio (PMR)). The four-element (two active and two parasitic elements) version of the HB9CV antenna was assembled. The electrical parameters were measured with a vector analyzer and presented. The four-element version of the HB9CV antenna was assembled. The most important steps in the assembly process, the materials used and their dimensions are described and commented. The electrical parameters of the assembled antenna were measured with a vector analyzer and presented.

HB9CV ANTENNA

The HB9CV antenna was developed in the 1950s by radio amateur Rudolf Baumgartner from Switzerland with the call sign HB9CV, after which the antenna was named. In its simplest form, the HB9CV, also known as Swiss antenna, consists of two unequal length dipoles that are fed by a matching device, i.e. phasing lines (Fig. 1). The distance between the two dipoles is one-eighth of a wavelength (1/8λ) (Fig. 1). According to the construction, the HB9CV antenna resembles the ZL-Special antenna [1, 2]. Also, the HB9CV antenna can be considered a Log-periodic antenna [1] in its simplest form (only two phased elements). The HB9CV antenna can be designed as a symmetrical system suitable for feeding by balanced lines (Fig.1.a [1]), or as an asymmetrical system suitable for feeding by unbalanced lines such as coaxial cables (Fig.1.b [1]). Given that coaxial cables are currently used exclusively for antenna power supply, in this paper, the focus will be on versions of the HB9CV antennas designed as an asymmetrical system.

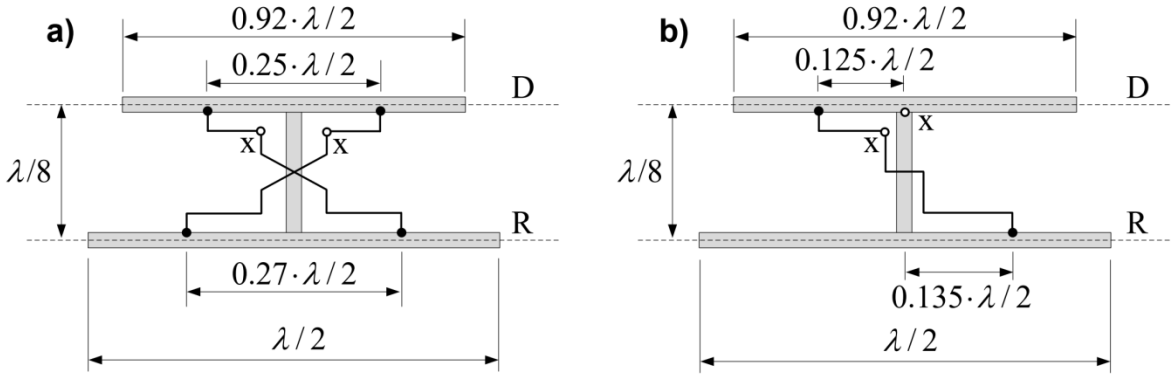


Fig. 1. *Two element HB9CV antenna, main dimensions and wiring, feeding point positions (marked with x-x) for: a) balanced lines, b) unbalanced lines*

Unlike the Yagi antenna, which has one active element (driver) that is powered by radio-frequency (RF) power, and the other elements are parasitic elements (reflector and directors), the HB9CV antenna has two active elements powered by RF power that perform the functions of director and reflector.

This approach has several advantages which can be explained as follows. Parasitic elements base their operation on the principle of re-emitting the RF energy they were exposed to. In this process of re-emitting RF energy, part of the energy is lost due to the skin effect in the conductors of the parasitic element. At the same time, parasitic elements are not exposed to all of the RF energy emitted by the active element (driver element), but only to a portion of that energy. Both of these phenomena reduce the effectiveness of parasitic elements in focusing radiation. By using two active elements (dipoles) of different dimensions and supplied with RF power with an appropriate phase shift, greater efficiency of the elements in focusing radiation is achieved. Due to the above, the HB9CV has a higher gain compared to a Yagi antenna for the same physical dimensions (boom length) [1]. Because of this advantage, radio amateurs develop a version of the HB9CV antenna with three active elements was developed. Although the HB9CV antenna with three active elements has a higher gain compared to the antenna with two active elements, and a better front/back radiation ratio, the main lobe in the radiation pattern from the front is significantly deflected from the longitudinal axis of the antenna. For this reason, this type of HB9CV antenna is rarely used, and to increase the gain and front/back radiation ratio, the use of parasitic elements is preferred.

Another advantage of the HB9CV antenna is that the dimensions of the elements of the HB9CV antenna are less critical compared to the Yagi antenna. Given that the position of the phase line connection to the elements can be made adjustable, it is possible to influence the electrical and electromagnetic parameters of the antenna.

In this way, it is possible to compensate to some extent the influence of inadequate dimensions of the antenna elements on the electrical and electromagnetic parameters of the antenna. By moving the position of the phase line connection to the elements, a point can be found where the real part of the antenna's wave impedance is exactly 50 ohms.
Almost regularly the HB9CV antenna has a reactive part of the wave impedance different from zero. However, the character of the reactive part of the antenna's wave impedance is such that it can be compensated by capacitive reactance. This can be achieved by adding a variable capacitor between one of the feeding points and the core of the coaxial cable (Fig. 2 [1]). The process of compensating the reactive part of the antenna's wave impedance, that is, improving voltage standing wave ratio (VSWR) is simple. Using a vector analyzer, the character of the antenna's wave impedance is monitored, and it is necessary to slowly change the capacitance of the variable capacitor until complete compensation of the reactive part of the wave impedance is achieved. Then it is necessary to unsolder the variable capacitor and measure its capacitance. Then, in place of the variable capacitor, a capacitor of fixed capacitance is soldered. A capacitor of fixed capacitance should have the capacitance that was measured on the variable capacitor.

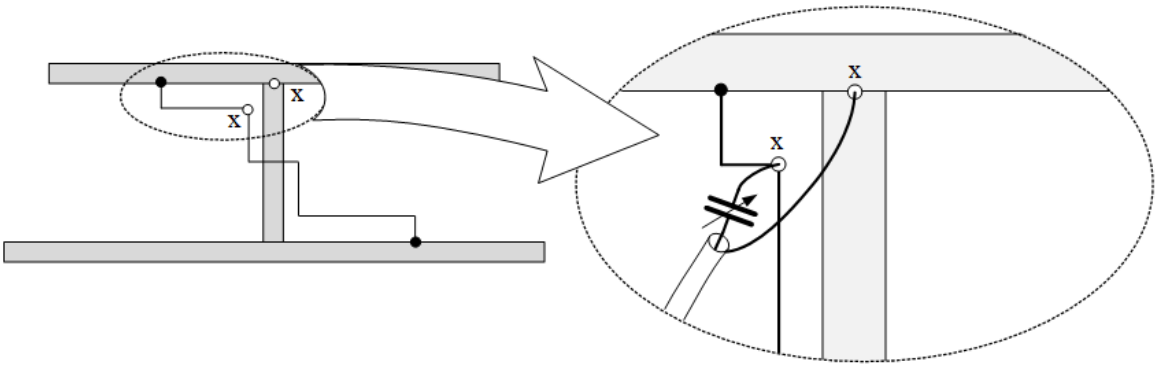


Fig. 2. *A detailed view of the feeding points and compensation of the reactive part of the antenna's wave impedance using a variable capacitor*

Since coaxial cable has a certain capacitance between the sheath and the core, coaxial cable can be used instead of a capacitor (Fig. 3). The required length is determined according to the technical data of the coaxial cable manufacturer on the capacity per unit length of the coaxial cable. Initially, a slightly longer piece of coaxial cable than necessary should be soldered, and then shortened in several steps until complete compensation of the active part of the antenna's wave impedance is achieved.

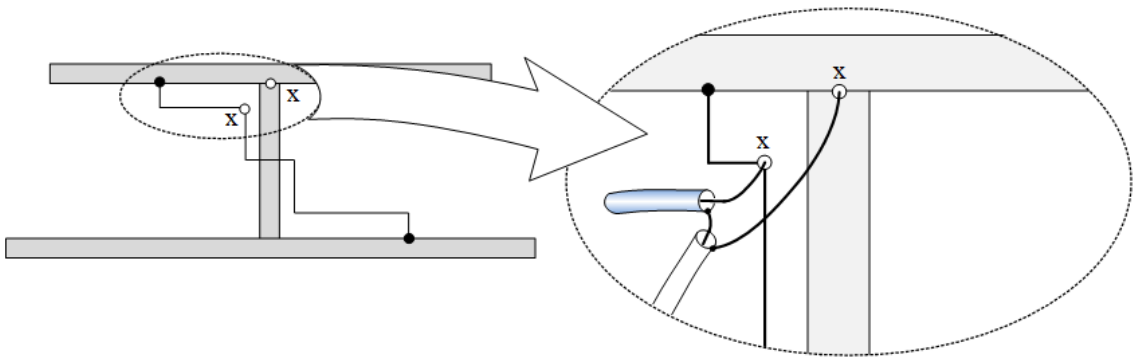


Fig. 3. *A detailed view of the feeding points and compensation of the reactive part of the antenna's wave impedance using pieces of coaxial cable*

NUMERICAL SIMULATION

Numerical calculation of the electromagnetic and electrical behavior of the antennas was carried out in the 4NEC2 software [8]. Numerical calculations were performed for the HB9CV antenna with two elements (Fig. 4.a) and four elements (Fig. 4.b). The numerical calculation was carried out for an operating frequency of 446 MHz. The obtained dimensions of the antenna elements and spacing are presented graphically (Fig. 4). The models of both antennas in the 4NEC2 software are shown in Fig. 5. The radiation diagrams are shown in Fig. 6 and Fig. 7.

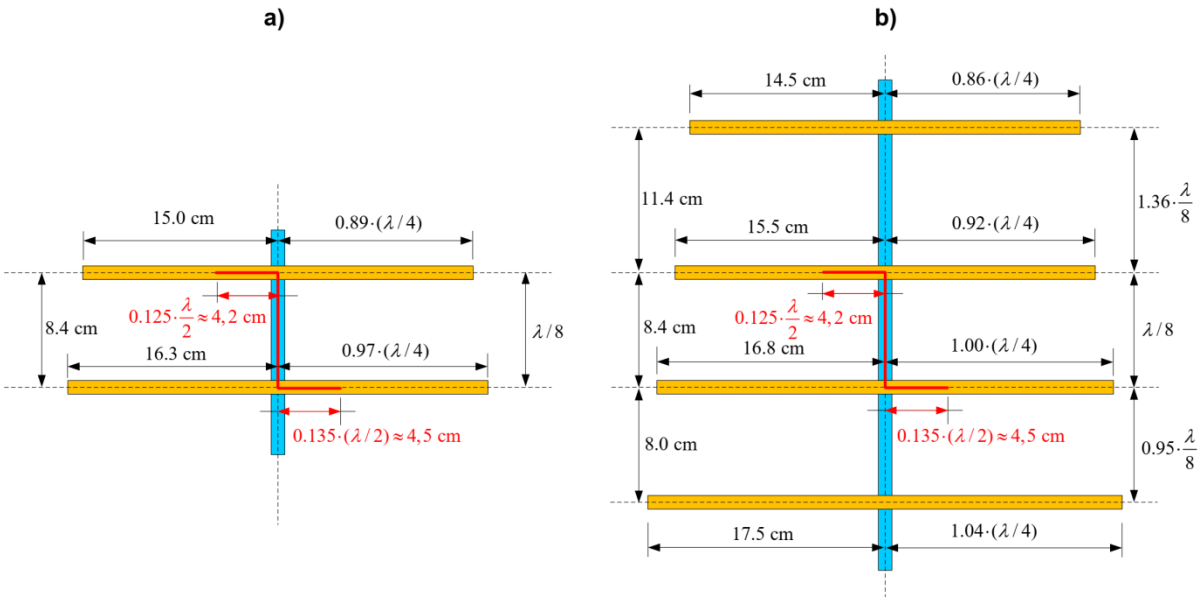


Fig. 4. *Dimensions and spacing obtained by numerical calculation for HB9CV antenna with a) two elements, b) four elements*

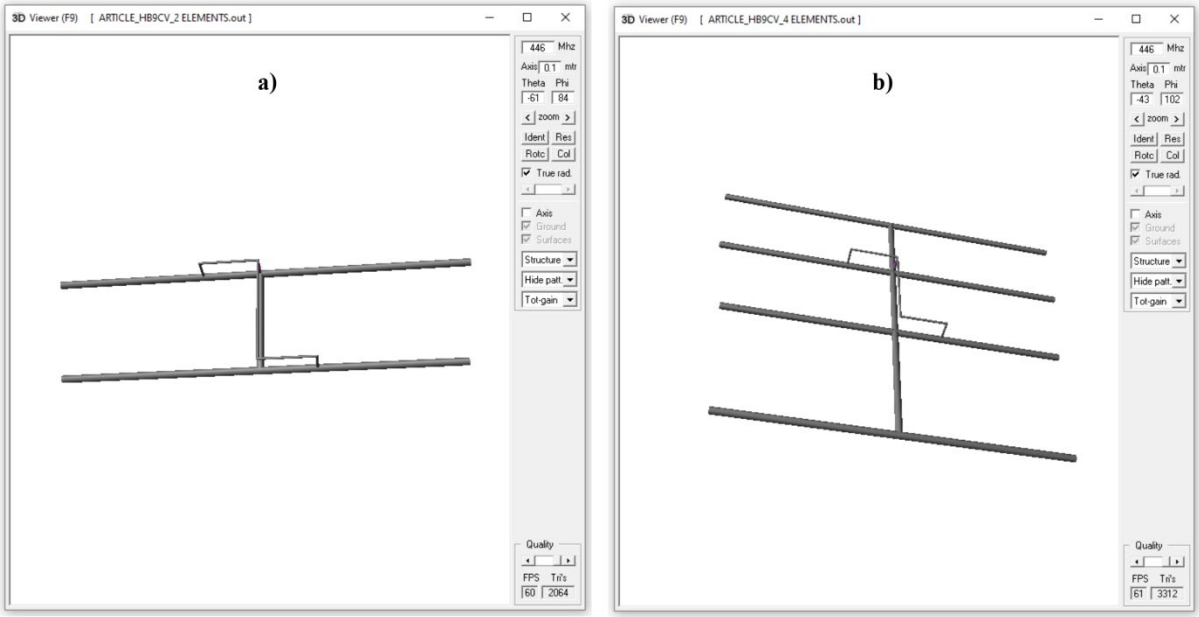


Fig. 5. *3D view of the HB9CV antenna model with a) two elements, b) four elements*

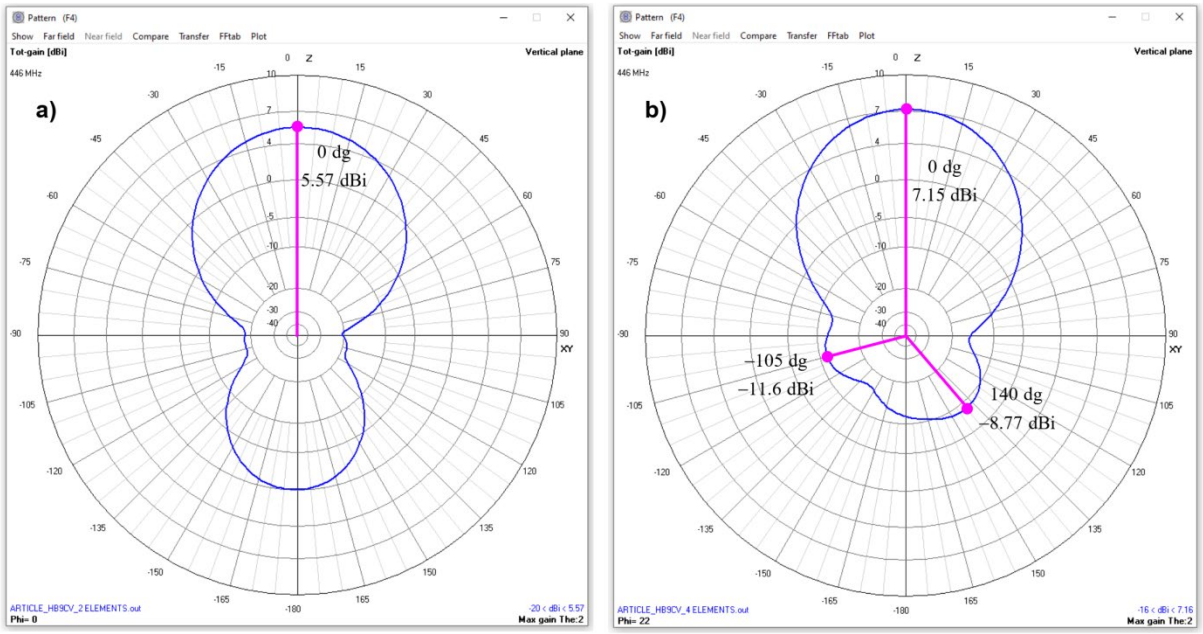


Fig. 6. *Two-dimensional radiation patterns (total gain in dBi) of the HB9CV antenna with: a) two elements and b) four elements*

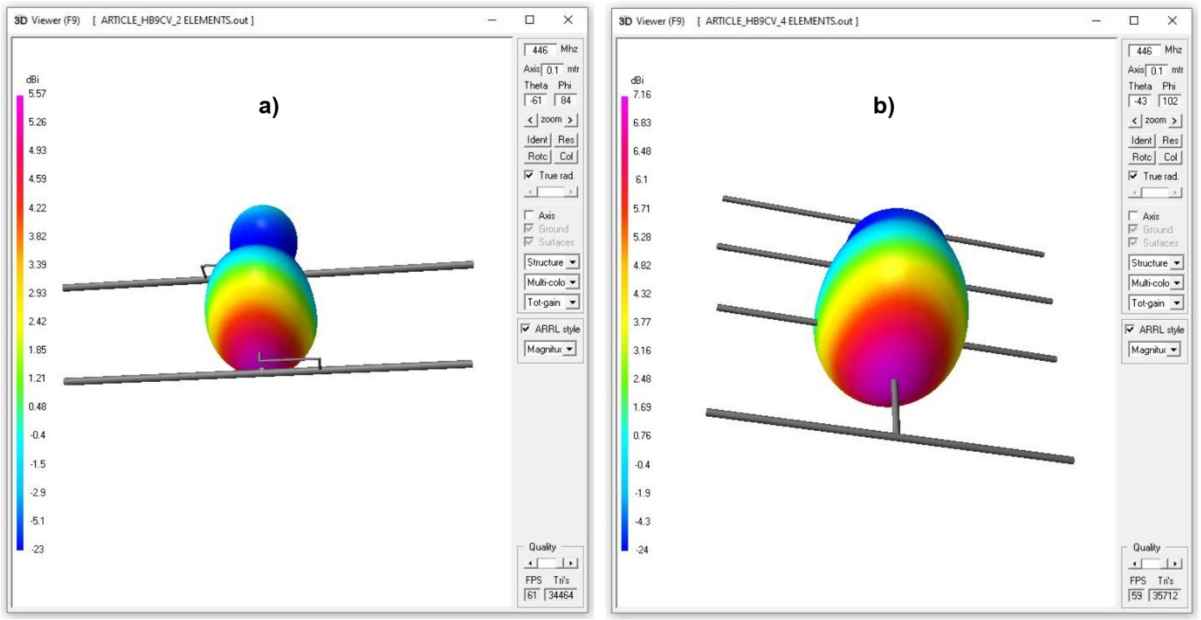


Fig. 7. *Three-dimensional radiation patterns (total gain in dBi) of the HB9CV antenna with: a) two elements and b) four elements*

ANTENNA ASSEMBLING AND PARAMETERS MEASUREMENT

On the basis of the carried out numerical calculation (Fig. 4.b), the HB9CV antenna with four elements was assembled (Fig. 8). All elements, active and parasitic are made of aluminium tube with diameter Φ=6 mm. A hollow aluminium tube with a square cross-section (dimensions of 1 cm x 1 cm) was used for the boom. The phasing line is made of solid aluminium wire with a diameter of 2 mm and is soldered to the active elements. The soldering of phasing lines and antenna elements is carried out with special electrodes for soldering aluminium [9]. A thin and very flexible RG174 coaxial cable [10], one meter long (measured from the feeding points to the SMA connector), is threaded through the handle and boom of the antenna.

In this way, the coax cable is not exposed to the radiation of the antenna elements, thereby reducing the probability of the appearance of common mode currents. Unintentional bending of the phasing lines is prevented by placing two plastic spacers (Fig. 9). Compensation of the reactive part of the wave impedance was achieved with a piece of RG174 coaxial cable with a length of 3 cm (Fig. 9). Initially, a piece of 6 cm long RG174 coaxial cable was soldered and shortened in several steps (initially by a centimetre, then half a centimetre, then in millimetres) until a voltage standing wave ratio (VSWR) at the operating frequency of 446 MHz below 1.5 was reached. The antenna, including the plastic handle and coaxial cable, weighs 160 g.



Fig. 8. *Handheld HB9CV antenna with four elements (two active elements and two parasitic elements). The antenna was assembled by the authors*



Fig. 9. *A detailed view of the plastic spacers, feeding points and compensation of the reactive part of the antenna's wave impedance using pieces of coaxial cable*

The electrical parameters of the assembled antenna were measured using the PS100 RF vector antenna analyzer meter [11]. At the operating frequency of 446 MHz, the wave impedance (after compensating for the reactive part) Z= 49.7+j17 Ohms was achieved (Fig. 10.a), which corresponds to VSWR of approximately 1.4 (Fig. 10.a). For VSWR ≤ 1.5, the bandwidth is approximately 25 MHz (Fig. 11.b), that is, for the frequency range in which the antenna operates excellently, with negligible RF power reflections. The usable bandwidth (for VSWR ≤ 2.0) is approximately 30 MHz (Fig. 10.b).

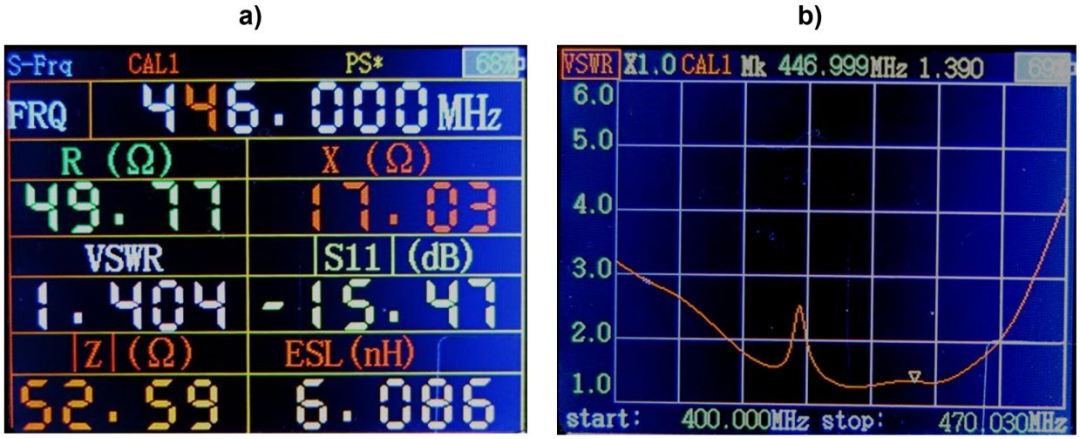


Fig. 10. *Measured parameters of a four element HB9CV antenna: a) basic electrical parameters, b) dependence of VSWR on frequency*

The gain measurement was performed by comparing the radiation intensity with a reference dipole. The measurement determined the front gain. The measured gain is approximately 1.5 decibel lower than the gain obtained by numerical calculation (Fig. 6.b). Part of the resulting difference is due to the attenuation of the RF power in the coaxial cable. According to [10], the attenuation in a one-meter-long RG174 coaxial cable is between 0.6 dB and 0.7 dB, the remaining difference is the discrepancy between the numerical calculation and the actual gain. In order to reduce RF power losses in coaxial cable, we recommend using the widely available RG58 coaxial cable [12], which has lower losses (between 0.4 dB and 0.5 dB per meter), but is slightly less flexible than RG147.

CONCLUSION

The HB9CV antenna has been around for more than seven decades among radio amateurs. Ease of manufacturing and assembly of the HB9CV antenna and HB9CV antenna family, excellent mechanical durability, and excellent electromagnetic and electrical characteristics are the reasons for its popularity and widespread use among radio amateurs. Paper demonstrated and confirmed the simplicity of the HB9CV antenna fabrication process. The HB9CV is simply tuned by moving the position of the phase line connection to the passive element and by trimming the coaxial cable, which is used as a capacitance to compensate the reactive part of the antenna's wave impedance. Also, the paper showed that adding parasitic elements to make reflectors and directors can further improve the characteristics of the basic HB9CV antenna. Adding parasitic elements to make reflectors improves the front to end radiation ratio. Adding parasitic elements to create directors improves gain and eliminates the inherent disadvantage of the HB9CV antenna of beam deflection relative to the boom axis. The aforementioned benefits of using additional parasitic elements are the reason for the widespread use of these technical solutions. In short, for all of the above reasons, the HB9CV antenna and its derivatives (HB9CV antenna family) are deservedly a very popular antenna among radio amateurs.

REFERENCES

[1] Rothammel, K.: Antennenbuch, Franckh, Stuttgart, 1978, ISBN-10: 344004498-X
[2] Sichla, F., (DL7VFS), Die HB9CV-Antenne, 1st edition, Verlag für Technik und Handwerk, 2003, ISBN: 3-88180-392-0
[3] Burberry, R. A.:VHF and UHF Antennas. In Institution of Engineering and Technology eBooks. https://doi.org/10.1049/pbew035e, 1992, ISBN: 978-0-863-41269-6
[4] Huang Y. and Boyle K.: Antennas: From Theory to Practice, Wiley, New Delhi, 2008, ISBN: 978-0-470-77292-8
[5] Barić, T., Glavaš, H., Hederić Ž.,: Handheld UHF Quad Antennas With Reinforced Mechanical Characteristics, Proceedings of the International Conference on Smart Systems and Technologies (SST 2022), pp. 281-288, Osijek, Croatia, 2022
[6] Barić, T., Glavaš, H., Mandrić, V.: Hybrid UHF Quad Antenna for Indoor Use, Proceedings of the International Conference on Smart Systems and Technologies (SST 2024) pp. 7-14. Osijek, Croatia, 2024, doi: 10.1109/sst61991.2024.10755507
[7] Barić, T., Glavaš, H.,: Maintaining Mobile Communication in Distress and Emergency Situations, Proceedings of the 32nd International Conference on Organization and Technology of Maintenance (OTO 2023), pp. 97-112, Osijek, Croatia, 2023, doi: 10.1007/978-3-031-51494-4_9
[8] 4NEC2 Homepage, https://www.qsl.net/4nec2, Last accessed 2025/02/10
[9] Aluminium soldering rods, datasheet available at: https://durafixonline.com/gb/, Last accessed 2025/02/10
[10] RG174 coaxial cables, Manufacturer: Bedea Berkenhoff & Drebes GmbH, Data Sheet available at: https:// www.bedea.com, Last accessed 2025/02/10
[11] PS100+, N1201SA series vector impedance analyzer, product manual, Homepage, https://img.banggood.com, Last accessed 2025/02/10
[12] RG58 coaxial cables, Manufacturer: Bedea Berkenhoff & Drebes GmbH, Data Sheet available at: https:// www.bedea.com, Last accessed 2025/02/10

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SIMULATED IoT SENSOR MONITORING AND ALERTING USING PYTHON AND WEB APIs

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Abstract: A software-only framework is presented for the simulation of Internet of Things (IoT) sensor streams and the coordination of real-time alerting via Python and web-based APIs. Synthetic data generators produce temperature, light, and humidity readings according to configurable statistical models and temporal trends. These readings are constantly checked against set limits, and when they go over those limits, automatic notifications are sent out through RESTful interfaces to services like Telegram and IFTTT. The suggested method eliminates the need for physical hardware, making it easier to quickly create prototypes, teach concepts, and test IoT alert systems in places with few resources. The framework's performance is tested using a simulation with 50 samples, showing that it can accurately detect events in under 2 seconds and reliably send alerts to outside channels. The results substantiate the utility of a virtualized IoT testbed for early-stage development and educational applications.
Key words: IoT simulation, Python-based alerting, synthetic sensor data, web API integration, virtual IoT testbed, real-time notifications.

INTRODUCTION

The rapid development of Internet of Things (IoT) technologies has reshaped residential, industrial, commercial, and healthcare sectors by enabling real-time monitoring, automation, and intelligent decision-making [1]. At the core of these systems are networks of sensors that capture essential parameters such as temperature, humidity, and luminosity, which are directly tied to thermal transfer, environmental control, and process efficiency [2]. In the context of energetics and process technique, the accurate measurement and analysis of these quantities are crucial for improving process stability, optimizing energy use, and ensuring environmental safety.

Despite their potential, the early development and testing of IoT applications are often constrained by the high cost and complexity of physical hardware [3]. To address these challenges, software-based IoT simulation frameworks have emerged as efficient and cost-effective alternatives for preliminary validation and education [4,5]. Python, with its readability and extensive scientific libraries such as Pandas, NumPy, and Matplotlib, provides a powerful platform for building such simulations [6, 7]. This paper presents a software-only framework that generates synthetic environmental data, detects threshold exceedances in real time, and dispatches alerts through APIs like Telegram and IFTTT [8]. The approach supports rapid prototyping, educational demonstrations, and process-oriented analysis in resource-limited environments.

RELATED WORK

Research on IoT simulation can be grouped into several main directions. Hybrid and hardware-in-the-loop simulation combines physical and virtual components, originally developed in structural engineering for studying nonlinear dynamic systems [9]. Later studies improved stability and accuracy of algorithms [10-12], while deep learning models were even applied to replace finite element solvers [13, 14]. Although designed for civil engineering, principles such as synchronized feedback and real-time logic are relevant for IoT simulators aiming to emulate

sensor behaviour and responses. A second direction is software-only sensor-network emulators, such as NS-3 [15] and CupCarbon [16], which model communication protocols and packet-level behaviour. While effective for network analysis, they focus less on sensor dynamics or alerting. Cloud-based approaches extend this by simulating sensors as virtualized services, supporting large-scale monitoring and control [17]. However, these solutions typically require access to real devices or testbeds, limiting their use in fully virtualized contexts. The third stream emphasizes Python frameworks as a flexible and accessible tool for scientific computing [18]. Libraries such as Pandas, NumPy, and Matplotlib allow efficient data handling, visualization, and API integration [6, 7]. In IoT, this enables software-only testbeds for generating sensor data, applying threshold-based logic, and sending notifications through RESTful services [19,20]. Despite this progress, a clear gap remains: lightweight frameworks that integrate virtual sensing, real-time evaluation, and automated alerting without reliance on hardware or proprietary platforms. The present work addresses this gap by introducing a Python-based environment tailored for education, prototyping, and process-oriented analysis.

SYSTEM ARCHITECTURE

The proposed framework reproduces the logic of an IoT sensing and alerting pipeline entirely in software. It consists of three main components: (1) a virtual sensor module, (2) a threshold evaluation engine, and (3) a notification and integration layer, with optional logging and visualization. All elements are implemented in Python to ensure transparency, modularity, and adaptability. The workflow, shown in Fig. 1, mirrors the sensing-processing-notification loop typical of real industrial and environmental monitoring systems.

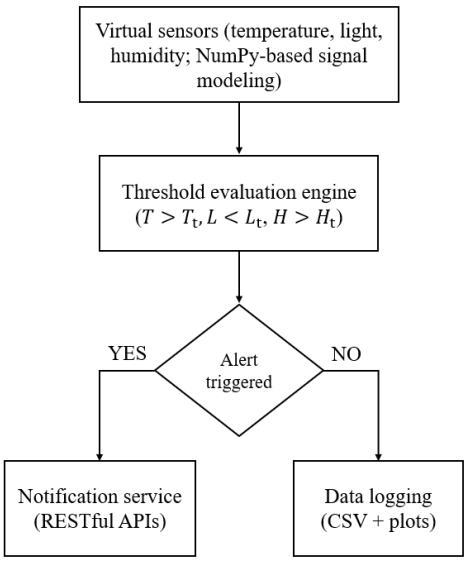


Fig. 1. *Logical flow of synthetic sensor data, threshold evaluation, alert dispatching, and optional logging in the proposed IoT simulation framework.*

The virtual sensor module generates synthetic readings of temperature, light intensity, and humidity-parameters that represent fundamental physical quantities in energetics and process engineering. Temperature values follow sinusoidal or stochastic trends, reflecting heat transfer governed by radiative and convective processes. Light intensity simulates diurnal illumination cycles and sudden attenuation (e.g., cloud cover), which directly influence thermal balance through absorption and re-radiation. Humidity is modelled as a gradual decrease or oscillatory trend, representing evaporation, ventilation, or moisture transport in air. Each sensor stream is configurable in terms of baseline, amplitude, and noise, making it possible to approximate realistic environmental dynamics. The threshold evaluation engine continuously compares simulated data against user-defined limits that mark critical process states (e.g., overheating, insufficient illumination, or low humidity). Such thresholds represent practical boundaries in

energetics and process technique - for instance, maximum operating temperature of materials, minimum light levels for efficient energy conversion, or humidity levels required for stability of sensitive processes. The evaluation engine, implemented through Python conditional logic, can be adapted for compound or time-dependent conditions, offering flexibility for different process scenarios. Once a threshold is crossed, the notification layer formats the event into an alert that includes sensor type, value, timestamp, and triggered condition. This alert is dispatched in real time via RESTful APIs (e.g., Telegram, IFTTT), mimicking the role of industrial supervisory systems that issue warnings when safety or efficiency margins are exceeded. In cases where thresholds are not exceeded, the framework records the data into structured CSV logs and optionally produces plots using Matplotlib. These visualizations highlight both normal operation and deviations, serving as an analogue to diagnostic charts in process monitoring.

IMPLEMENTATION

The framework was realized entirely in Python, relying on open-source libraries that support numerical modelling, control logic, communication through RESTful APIs, and visualization. All components operate locally on a standard computer, which eliminates the need for specialized hardware or cloud services and makes the system easy to reproduce in different environments.

To emulate the behaviour of environmental variables relevant for energetics and process technique, three types of virtual sensors were implemented: temperature, light intensity, and humidity. Their evolution in time is described by mathematical functions that capture realistic physical trends. Temperature follows sinusoidal variations that resemble diurnal heating and cooling cycles, while additional random noise introduces local fluctuations similar to microclimatic effects. Humidity can be modelled as an exponential decrease, representing evaporation or ventilation, whereas light intensity is described by periodic changes that emulate solar irradiation modulated by cloud cover or shading. By adjusting parameters such as baseline values, amplitudes, and noise levels, it becomes possible to reproduce both stable and highly dynamic conditions, creating a versatile testbed for analysing process behaviour.

The simulated data streams are continuously evaluated against predefined thresholds that correspond to critical points in physical systems. For example, maximum allowable temperature for material stability, minimal light levels required for energy conversion efficiency, or humidity levels necessary for maintaining environmental balance. When one of these thresholds is exceeded, the framework immediately triggers an alert, thereby reproducing the way industrial supervisory systems signal the crossing of operational limits. These alerts are dispatched in real time through web-based services such as Telegram or IFTTT, which act as communication channels between the simulated process and the operator.

In addition to alerting, the system records all sensor values and events into structured log files, enabling further analysis of temporal behaviour. The data can be visualized through time-series plots with marked thresholds and alert instances, providing an intuitive picture of process evolution and deviations. Depending on the needs of the user, the simulation can be executed in two different modes: in batch mode, where a finite number of samples is generated for offline inspection, or in real-time mode, where data streams evolve continuously with delays that mimic real sensor readings. Both approaches support applications in education, early-stage research, and practical process analysis.

RESULTS AND DISSCUSION

The simulation results highlight the physical nature of the monitored parameters (temperature, light intensity, and humidity) and demonstrate how their variations can be meaningfully translated into alerts. Rather than being treated as abstract data, these variables reflect processes such as radiative heating, evaporative cooling, and atmospheric attenuation, all of which are central to energetics and process technique. By mapping their temporal behaviour against defined thresholds, the framework captures moments when conditions deviate from

safe or efficient regimes and triggers alerts accordingly. The time series in Fig. 2 illustrates these dynamics.

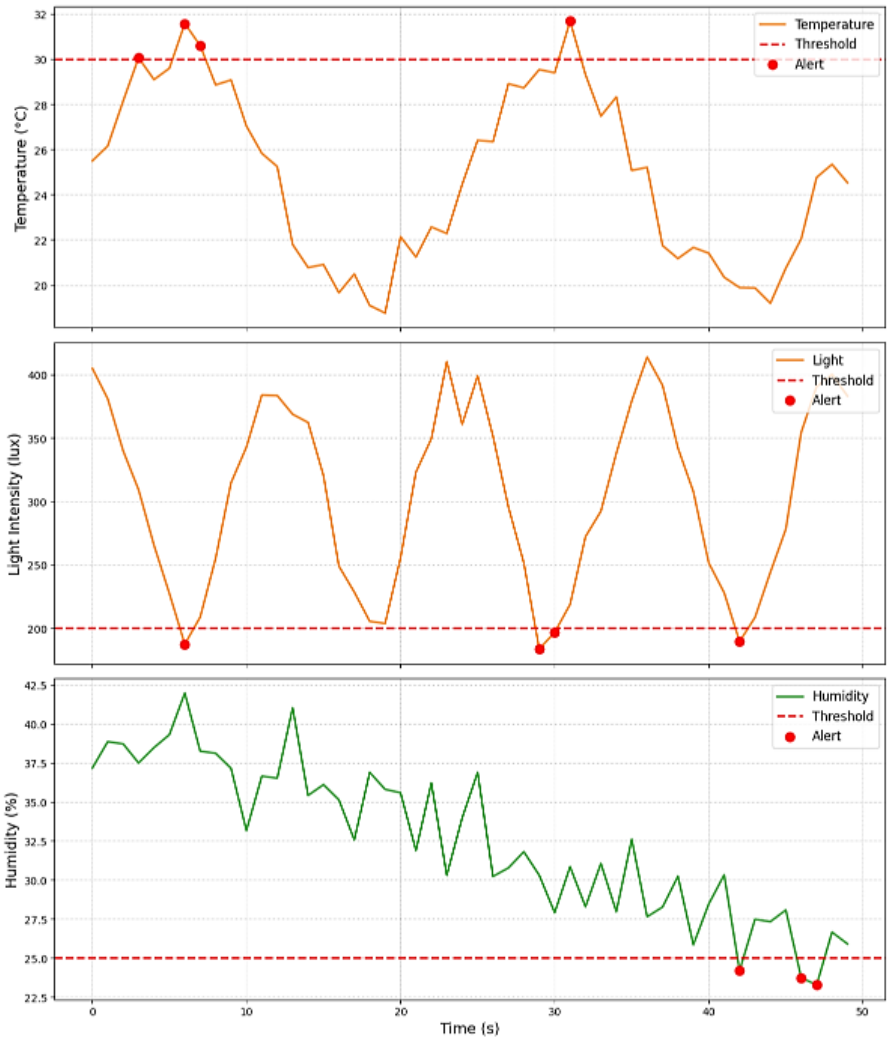


Fig. 2. *Simulated time series of environmental parameters over a 50-second interval, illustrating dynamic behavior of temperature, light intensity, and relative humidity. Each subplot includes a dashed red line indicating the predefined threshold for alert activation: 30 °C for temperature, 200 lux for light, and 25% for humidity. Red circular markers denote the precise instances of threshold exceedance, triggering automated alerts.*

Temperature follows an oscillatory trend with peaks occasionally surpassing the critical value of 30°C, representing conditions where thermal stress may impair materials or biological systems. Light intensity exhibits periodic fluctuations consistent with illumination cycles, with rapid dips simulating shading effects; when values fall below 200 lux, the system identifies insufficient illumination for reliable operation. Humidity decreases gradually to represent drying, with the 25% threshold marking the onset of unfavourable environmental conditions. The close alignment of alerts with physical threshold crossings demonstrates the robustness of the detection mechanism and its resistance to noise. When examined together, the three parameters reveal strong coupling. As shown in Fig. 3, increases in light intensity often drive temperature rises, while reduced humidity amplifies thermal stress by limiting evaporative cooling. This multivariate view underscores the importance of cross-parameter analysis: adverse conditions are rarely the result of a single variable but emerge from their combined influence.

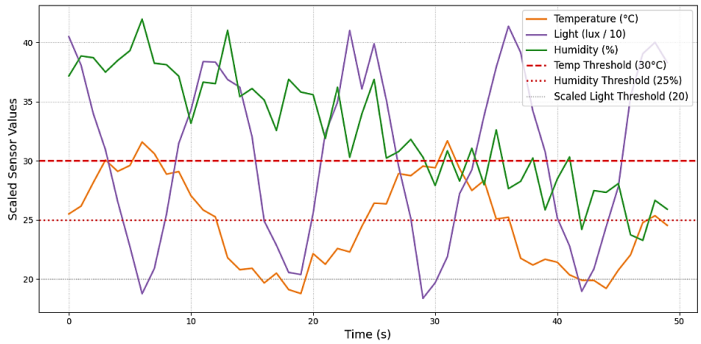


Fig. 3. *Overlay of normalized sensor readings illustrating the concurrent evolution of temperature (orange), light intensity scaled by a factor of 10 (purple), and humidity (green) over the simulation duration. Horizontal dashed lines mark respective alert thresholds for temperature (30 °C), light intensity (200 lux), and humidity (25%).*

The temporal distribution of alerts in Fig. 4 further illustrates this point. Temperature and light thresholds are often exceeded simultaneously, signalling periods of intense radiative forcing, while humidity alerts appear later, reflecting slower but cumulative drying processes. Such concurrency of alerts mirrors real-world compound stress events, for example heat waves coupled with low humidity, which can degrade materials, reduce efficiency, or threaten human safety.

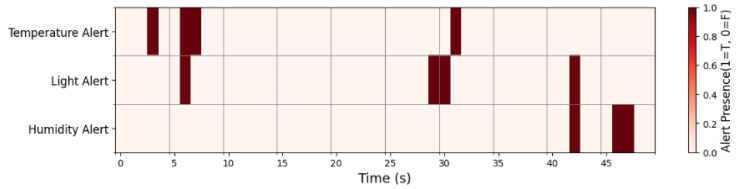


Fig. 4. *Heatmap representation of alert states across the three monitored parameters. Rows correspond to sensor channels, temperature, light, and humidity, while columns represent successive time points. A value of 1 (dark red) indicates that the respective parameter has breached its critical threshold at that moment; 0 (pale) denotes nominal conditions.*

Figures 5 and 6 extend the analysis by projecting the data into phase spaces. The temperature-humidity plot identifies regions where elevated heat coincides with insufficient moisture, marking zones of compounded risk. The light-temperature-humidity interaction map highlights how illumination drives heating differently under moist and dry conditions, with the most severe stresses occurring when high light, high temperature, and low humidity overlap. These compound risk zones are of particular importance in process monitoring, as they pinpoint operating regimes where failure is most likely to occur.

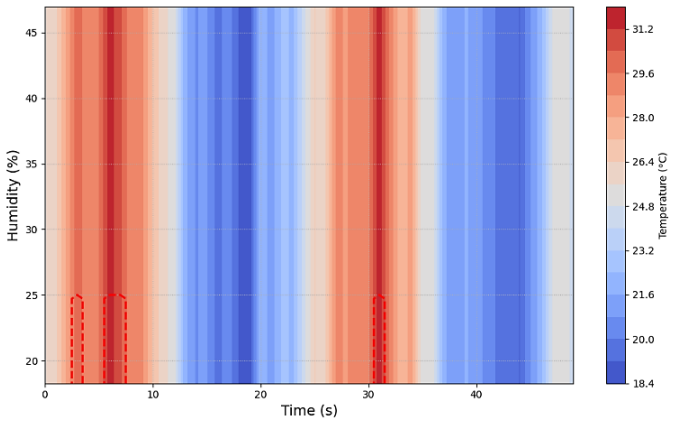


Fig. 5. *Two-dimensional contour map of temperature (color-coded) plotted against time (x-axis) and humidity (y-axis). The dashed red horizontal line marks the humidity alert threshold at 25%.*

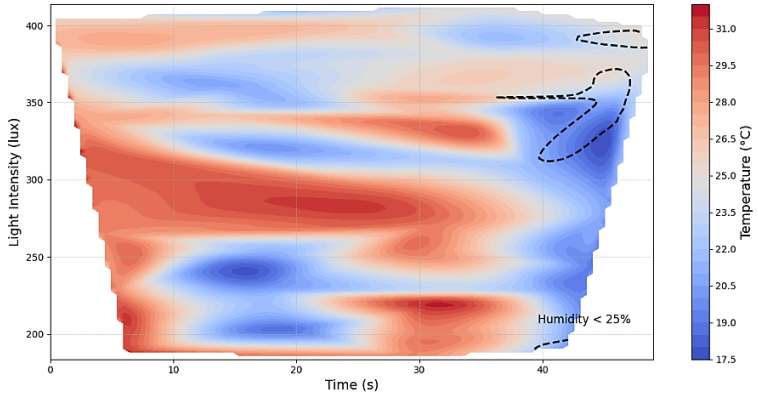


Fig. 6. *Three-dimensional contour visualization of temperature variation (color scale) over time and light intensity. Dashed black contours indicate regions where relative humidity falls below the critical 25% threshold.*

Taken together, the results presented in this Section demonstrate that a purely software-based simulation can capture both the physics of environmental variability and the logic of IoT-driven detection. The framework therefore provides a practical and low-cost testbed for analysing process dynamics, anticipating critical states, and designing alert strategies relevant to energetics and process technique.

CRITICAL ASSESSMENTS OF THE PROPOSED FRAMEWORK

The proposed framework offers clear advantages for studying IoT-based monitoring in energetics and process technique. By simulating temperature, light, and humidity entirely in software, it enables the exploration of key physical quantities that govern heat transfer, illumination efficiency, and moisture control, all without the cost or complexity of real sensors. Its modular Python design provides a reproducible environment for both research and teaching, while API-based notifications mirror the logic of industrial supervisory systems. At the same time, the framework has limitations. It does not reproduce imperfections of real transducers (e.g., drift or hysteresis) or network effects such as latency and packet loss. Its reliance on simple threshold rules, though transparent, cannot capture the adaptability of modern process monitoring strategies that increasingly rely on predictive or machine learning approaches. These constraints, however, suggest clear directions for further work. Hardware-in-the-loop extensions could bring the simulation closer to real process validation, probabilistic alerting would better capture environmental variability, and integration with network emulators could combine physical modelling with communication analysis. In this way, the framework can evolve into a more powerful tool for designing and testing resilient monitoring strategies in energetics and process technique.

CONCLUSION

This study presented a Python-based framework that emulates IoT sensing and alerting workflows entirely in software. By simulating temperature, humidity, and light intensity the framework provides a reproducible and low-cost platform for analysing how environmental variables evolve, cross critical thresholds, and trigger automated alerts. The results show that both univariate and multivariate behaviours can be represented in a way that highlights the physical coupling of heat transfer, illumination, and moisture control.
The approach is valuable for both teaching and early-stage research: it allows algorithm validation and systems-level thinking without the need for physical hardware, while API-based notifications reproduce the logic of industrial supervisory systems. Future work will focus on enhancing realism by introducing stochastic hardware effects, adaptive alerting, and integration with cloud infrastructures. In doing so, the framework can grow into a versatile tool

not only for IoT prototyping and education, but also for exploring and optimizing monitoring strategies in energy and process-oriented applications.

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REFERENCES

[1] Gubbi, J., Buyya, R., Marusic, S., Palaniswami, M., Internet of Things (IoT): A vision, architectural elements, and future directions, Future Generation Computer Systems, Vol.29, No.7, pp.1645-1660, 2013.
[2] Lee, I., Lee, K., The Internet of Things (IoT): Applications, investments, and challenges for enterprises, Business Horizons, Vol.58, No.4, pp.431-440, 2015.
[3] Atzori, L., Iera, A., Morabito, G., The Internet of Things: A survey, Computer Networks, Vol.54, No.15, pp.2787-2805, 2010.
[4] Mineraud, J., Mazhelis, O., Su, X., Tarkoma, S., A gap analysis of Internet-of-Things platforms, Computer Communications, Vol.89, pp.5-16, 2016.
[5] Yassein, M.B., Mardini, W., Khalil, A., Smart homes automation using Z-wave protocol, Proc. International Conference on Engineering & MIS (ICEMIS), IEEE, pp.1-6, 2016.
[6] McKinney, W., Data structures for statistical computing in Python, SciPy, Vol.445, No.1, pp.51-56, 2010.
[7] Hunter, J.D., Matplotlib: A 2D graphics environment, Computing in Science & Engineering, Vol.9, No.3, pp.90-95, 2007.
[8] Bröring, A., Seeger, J., Papoutsakis, M., Fysarakis, K., Caracalli, A., Networking-aware IoT application development, Sensors, Vol.20, No.3, pp.897, 2020.
[9] Takanashi, K., Udagawa, K., Seki, M., Okada, T., Tanaka, H., Nonlinear earthquake response analysis of structures by a computer-actuator on-line system, Bulletin of Earthquake Resistant Structure Research Center, Vol.8, pp.1-17, 1975.
[10] Chen, C., Ricles, J.M., Marullo, T.M., Mercan, O., Real-time hybrid testing using the unconditionally stable explicit CR integration algorithm, Earthquake Engineering & Structural Dynamics, Vol.38, No.1, pp.23-44, 2009.
[11] Kolay, C., Ricles, J.M., Marullo, T.M., Mahvashmohammadi, A., Sause, R., Implementation and application of the unconditionally stable explicit parametrically dissipative KR-α method for real-time hybrid simulation, Earthquake Engineering & Structural Dynamics, Vol.44, No.5, pp.735-755, 2015.
[12] Chae, Y., Kazemibidokhti, K., Ricles, J.M., Adaptive time series compensator for delay compensation of servo-hydraulic actuator systems for real-time hybrid simulation, Earthquake Engineering & Structural Dynamics, Vol.42, No.11, pp.1697-1715, 2013.
[13] Bas, E.E., Moustafa, M.A., Real-time hybrid simulation with deep learning computational substructures: System validation using linear specimens, Machine Learning and Knowledge Extraction, Vol.2, No.4, pp.469-489, 2020.
[14] Zhang, X., Xie, X., Tang, S., Zhao, H., Shi, X., Wang, L., Wu, H., Xiang, P., High-speed railway seismic response prediction using CNN-LSTM hybrid neural network, Journal of Civil Structural Health Monitoring, Vol.14, No.5, pp.1125-1139, 2024.
[15] Alam, T., Cloud-based IoT applications and their roles in smart cities, Smart Cities, Vol.4, No.3, pp.1196-1219, 2021.

[16] Chernyshev, M., Baig, Z., Bello, O., Zeadally, S., Internet of Things (IoT): Research, simulators, and testbeds, IEEE Internet of Things Journal, Vol.5, No.3, pp.1637-1647, 2017.
[17] Li, S., Tryfonas, T., Li, H., The Internet of Things: A security point of view, Internet Research, Vol.26, No.2, pp.337-359, 2016.
[18] Sun, Q., Berkelbach, T.C., Blunt, N.S., Booth, G.H., Guo, S., Li, Z., Liu, J., McClain, J.D., Sayfutyarova, E.R., Sharma, S., Wouters, S., PySCF: the Python-based simulations of chemistry framework, Wiley Interdisciplinary Reviews: Computational Molecular Science, Vol.8, No.1, p.e1340, 2018.
[19] Krishnamurthy, J., Maheswaran, M., Programming frameworks for Internet of Things, Internet of Things, Morgan Kaufmann, pp.79-102, 2016.
[20] Li, S., Xu, L.D., Zhao, S., The Internet of Things: A survey, Information Systems Frontiers, Vol.17, pp.243-259, 2015.

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DESIGN PRINCIPLES FOR A STANDARDIZED MUZZLE RISE TEST RIG

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Abstract: Muzzle rise is a critical factor affecting firearm accuracy, controllability, and hit rate, with its magnitude being highly dependent on weapon geometry. Improving the management of muzzle rise is, therefore, a key objective for arms manufacturers seeking to enhance weapon performance. This study addresses the need for standardized measurement by outlining the fundamental design principles and essential parameters for an effective muzzle rise test apparatus. It proposes a framework for a rig capable of providing reliable, quantitative data on muzzle dynamics to aid in future weapon design and evaluation.
Key words: firearms, muzzle rise, hit rate, accuracy, test rig

INTRODUCTION

The reliability and effectiveness of equipment used in infantry rifles are fundamental elements of operational success on the modern battlefield. Therefore, multi-dimensional testing processes are conducted to demonstrate the military standard compliance, durability, and functional adequacy of such equipment. These tests aim to measure the performance of equipment under harsh environmental and operational conditions, covering not only laboratory conditions but also realistic combat scenarios [1, 2].
Weapon accessories (optical systems, night vision devices, laser designators, holographic and red-dot sights) enhance the user's target acquisition capability and firing accuracy, while stocks and ergonomically designed support equipment improve weapon control and user comfort. Barrel-mounted accessories such as compensators, flash hiders, suppressors, muzzle brakes, and similar devices play a critical role in reducing recoil, concealing the shooter's position, and optimizing range/accuracy characteristics. This diversity demonstrates that equipment selection directly determines the user's effectiveness, safety, and operational efficiency [3].
Equipment evaluation can be grouped under three main categories, which can be listed as environmental, mechanical and functional tests. Environmental Tests measure the functionality of equipment under harsh conditions such as extreme temperatures, humidity, condensation, dust and sand. Conducted using MIL-STD-810 standards, IP codes and similar methods, these tests aim to prove the product's reliability and durability in the field. Mechanical Tests evaluate the structural integrity and endurance limits of equipment through vibration, impact, shock and drop tests. Methods such as sinusoidal and random vibration tests reveal potential resonance issues and deformations that may occur during prolonged use. Functional Tests: Equipment technical specifications are examined through ballistic, metallurgical, electrical, and optical tests. The zeroing consistency of sights, illumination, and the functionality of electronic components are also evaluated within this scope [4].
This multi-layered testing process ensures not only the reliability of the equipment but also its adaptability to technological developments, quality control, and standardization. Consequently, the meticulous selection and comprehensive testing of all equipment used in infantry rifles is critical for both the safety of military personnel and the sustainable success of operations [5].
Small arms is a term that encompasses both pistols and rifles, where barrel retraction is a critical factor influencing weapon controllability and the accuracy of successive shots. Despite its significance, no standardized metric currently exists to quantify this phenomenon. Barrel retraction is intrinsically linked to the weapon's internal design, meaning that even firearms with comparable calibers, weights, and external geometries can demonstrate markedly different retraction characteristics. This variability underscores the necessity of standardizing its measurement and incorporating it into formal technical specifications [6, 7].

This study presents a design framework for a test apparatus intended to integrate the assessment of barrel retraction into the weapon selection protocols used by national agencies. For such a standard to be internationally viable, the defined criteria must be objectively measurable and repeatable across different testing environments. The proposed system was developed with a focus on its core functional elements, operational principles, and overall suitability for providing reliable, quantitative data on retraction dynamics.

MATERIAL AND METHODS

The physical cause of muzzle rise is torque and the resulting imbalance. When the line of action of the recoil force generated by the firing of the bullet remains above the weapon's center of gravity or grip line, it causes the barrel to rotate upwards (pitch/muzzle rise). In addition, the flow of gas at the muzzle and the direction of the gas can also generate additional torque. The recoil impulse and peak force are fundamental parameters related to muzzle rise.

Military Equipment Standardization

Within the international defense industry, countries shape their procurement preferences based on operational requirements, geographical conditions and climatic factors. However, despite this diversity in preferences, the production and testing of military equipment is carried out within the framework of universal standards that guarantee reliability, interoperability and operational effectiveness. The testing processes for military equipment, including infantry rifles, are generally subject to strict protocols established by internationally recognized military institutions and standardization organizations. These military standards can generally be examined under three main categories: NATO Standards, American Standards (USA) and International Standards.

NATO Standards (STANAG)

NATO (North Atlantic Treaty Organization) standards consist of Standardization Agreement (STANAG) documents that aim to enhance the interoperability and operational effectiveness of allied member countries' military equipment. These standards contain comprehensive rules and requirements established to ensure the compatibility, reliability, and performance of equipment. Some of the prominent NATO standards in the context of infantry rifles are as follows:
STANAG 4172: Defines the technical specifications for Standard 5.56x45mm ammunition and the performance and durability test criteria for infantry rifles using this ammunition.
STANAG 4218/4219: This standard defined as Accelerometer Test Procedure for an Aircraft Inertial Navigation System which was renewed.
STANAG 4366/2333: Covers standards for combat clothing and their testing conditions.
STANAG 4375/4757/AOP 4157: NATO's test standards for weapons and ammunition
STANAG 4509: Technical Performance Specification Providing for the Interchangeability of 5.7 Mm X 28 Ammunition - Aop-4509 Edition A [8].

American Military Standards (MIL-STD)

American military standards (Military Standard - MIL-STD) are a comprehensive set of criteria established by the US Department of Defense (DoD) for the design, production, testing and evaluation of all military equipment. These standards were developed to meet the needs of US military units and to ensure that equipment used in operations is highly reliable. The basic MIL-STDs related to infantry rifles are as follows:
MIL-STD-810G: Provides a series of methods for testing the equipment's resistance to various environmental conditions such as extreme heat/cold, humidity, vibration, shock, dust, salt fog, etc. [9].

MIL-STD-1911: Standardizes safety and functional tests for firearms for example, trigger pull test, drop test [10]
MIL-STD-461: Ensures that weapon systems carrying electronic equipment do not experience problems interacting with other devices by specifying test requirements for electromagnetic interference (EMI) and electromagnetic compatibility (EMC) [11].

International Standards

This category includes standards published by various international standards organizations that broadly define the quality, reliability, and performance of military equipment. These standards are vital for facilitating international cooperation and ensuring the global compatibility of equipment. The relevant organizations and standards are as follows:

International Organization for Standardization (ISO) [12]:
ISO 9001: A quality management system standard that provides the basic framework for quality management of production and testing processes.
ISO 12232: Contains standards for measuring and evaluating the performance of optical and imaging systems (night vision goggles, laser pointers, etc.).
ISO 9227: Aims to measure the corrosion resistance of materials by standardizing the neutral salt spray (salt mist) test method.
In summary, modern military equipment, including infantry rifles, undergoes rigorous testing and quality control processes defined by established standards such as NATO, MIL-STD and ISO/IEC to ensure the successful execution of operational tasks. These standards form the basis for forces in different geographical locations to conduct joint operations with confidence in the performance and reliability of their equipment.

RESULTS AND DISCUSSION

Standards such as STANAG 4366 and MIL-STD-1911 detail the current methodologies for testing recoil, muzzle rise, and firing stability. These phenomena are primarily addressed within the context of shooting safety or functional performance testing. In contrast, academic literature provides a broader examination of weapon dynamics, ballistics, control systems, and measurement techniques. While tools like high-speed cameras, laser sensors, and accelerometers are commonly employed to quantify recoil, existing standards lack a comprehensive and detailed definition of the recoil phenomenon itself. Consequently, these standards may require revision to keep pace with technological advancements.
The foundation of any effective standard lies in its use of measurable metrics that yield consistent and repeatable results. Key metrics for quantifying recoil include angular displacement, angular velocity, stabilization time, vibration spectrum, and the establishment of repeatable test conditions.
Angular displacement is the maximum vertical angle the barrel reaches from its initial position that can be measured in degrees or milliradians. Angular velocity is the rate at which the barrel moves upward. Stabilization time is the duration required for the weapon to return consistently to its original target position after firing. Lastly repeatable conditions mean the test setup which must maintain constant parameters, such as locking torque, trigger pull force, and buttstock weight across all tests.
In aim to define more sophisticated engineering parameters, the concept of Degrees of Freedom (DoF) is critical. A test setup allowing rotation along the horizontal axis enables a more realistic analysis of recoil dynamics during firing. Inertial Measurement Units (IMUs) is one the sophisticated engineering parameters in which sensors such as accelerometers and gyroscopes were integrated onto the weapon or fixture are essential for high-precision measurement of angular velocity and acceleration. High-Speed Cameras are in common usage for ultimate fast action like gun firing. These systems visually record motion for subsequent analysis with motion-tracking software. Laser and Optical Sensors can track the displacement of a reference point on the weapon or a target at a distance. The weapon should

be stabilized either by a robotic arm that simulates a human grip or by being secured in a rigid vise. A significant design challenge involves developing an automatic trigger pull mechanism that applies a consistent force and speed for every test.
Following the setup's completion, data must be collected over several hundred shots to ensure statistical significance. The mean, standard deviation, and confidence intervals of this data should be analyzed to guide necessary optimizations to the apparatus. This process of firing tests and data collection is iterative, repeated until the setup is fully optimized. Throughout this phase, comparing experimental data with existing literature is crucial for the academic validation of the methodology.
The setup's validity will be demonstrated by its consistent ability to differentiate between weapon classes, specifically defined here as high muzzle-rise and low muzzle-rise weapons and to produce results that represent the behavioral extremes of these classes.
Once the method and experimental setup are matured, it would be advantageous to engage with standardization bodies (e.g., NATO, ISO, TSE) to develop formal technical proposals for new test standards.
Given that the apparatus contains high-energy moving parts and a live firearm, operational safety is paramount. The entire system must be designed to be remotely controlled and operated. Furthermore, to ensure widespread adoption, the setup must be cost-effective and easily repeatable by other testing laboratories.
Recoil and muzzle motion dynamics within this new setup can be modeled using physical numerical analyses, such as multi-body dynamics and elastic structural modeling. While these numerical models ultimately require validation against live-fire data, they are invaluable during the initial design phase. They provide powerful predictive capabilities and yield critical approximate results, especially when experimental testing is prohibitively expensive, dangerous, or logistically challenging. Such analyses allow for the examination of key parameters like mass, moments of inertia, and recoil forces through dynamic, static, rigid, and rigid-elastic simulations [13, 14].
Subsequent to numerical modeling, controlled studies can be conducted using safe propulsion sources, such as gas injection or thrust mechanisms, instead of live ammunition to examine the setup's behavior further.
Throughout this design process, factors of safety, ethical responsibility, and production quality control must be prioritized above all else.

CONCLUSION

In order to increase firing accuracy in firearms, the following points should be considered when designing an experimental setup aimed at reducing recoil.
1- In a recoil test setup, multiple metric values such as acceleration, angular displacement, and impulse should be measured; relying on a single value could lead to misleading results.
2- The setup should be suitable for different firearms, using the same ammunition, identical firing conditions, and a sufficient number of repetitions, with calibration of measurements documented.
3- Both shooter ergonomics and barrel gas behaviour should be examined together. Factors such as noise should be measured if necessary — some solutions (muzzle brakes) may be very good on their own but can create disadvantages in practical use (side gas, noise, side effects).
4- International safety criteria must be met.
5- Operating costs should be kept low, as the cost per shot becomes a significant parameter in scenarios involving numerous repeated firings.

REFERENCES

[1] Korniienko, I., S. Korniienko, V. Dmytriiev, A. Pavlenko, and D. Kamak. Investigation of the Model of Testing for Weapons and Military Equipment. 2021. Cham: Springer International Publishing.

[2] Haydak, V., Y. Karpenko, O. Chebakov, S. Chebotar, and I. Haydak, The Usa's Experience in Testing and Certification of Weapons and Military Equipment at Training Grounds. Наукові праці Державного науково-дослідного інституту випробувань і сертифікації озброєння та військової техніки, 2025. 24(2): p. 146-155.
[3] Transvaro, Product Catalog. 2025, Transvaro Elektron Aletleri Sanayi ve Ticaret A.Ş: Istanbul.
[4] Junker, V.J., Environmental Testing Standardization Via Mil-Std-810, Aeronautical Systems Div Wright-Patterson Afb Oh Directorate of Engineering Tests. 1962, Defense Technical Information Center.
[5] Ilhak, B. and F. Güner, Failure Analysis of Boron Carbide-Reinforced Rolled Homogeneous Armour Against Kinetic Energy Ammunition. Transactions of the Indian Institute of Metals, 2022. 75(7): p. 1831-1841.
[6] Güner, F., Hafif Silahlar ve Balistik. 2019: Nobel Bilimsel Eserler.
[7] Demir, M. and F. Güner, Materials and Manufacture Processes of Assault Rifle Barrels, in Measurement, Analysis and Manufacturing for Engineering Systems, M. MAKARACI, Editor. 2023, Bidge Publishing: Ankara.
[8] Standards Manager Web Standards List NATO-North Atlantic Treaty Organization. 2024, Hercules Ebooks Institute: Tabriz.
[9] (ATEC), U.S.A.T.a.E.C., Department of Defense Test Method Standard: Environmental Engineering Considerations And Laboratory Tests. 2008.
[10] (ATEC), U.S.A.T.a.E.C., Military Standard: Hand-Emplaced Ordnance (Heo) Design, Safety Criteria For. 1993.
[11] (ATEC), U.S.A.T.a.E.C., Military Standard: Electromagnetic Interference Characteristics Requirements For Equipment. 1967.
[12] Standards. 2024 [cited 2025 14.09.]; Available from: https://www.iso.org/standards.html.
[13] Bekircan, B. and F. Güner, FEA of stress distribution in firearms: evaluation of composite materials for gun slides. 2025. 67(9): p. 1423-1430.
[14] Güner, F., Numerical Investigation of AISI 4140 Powder High Relative Density Compaction In Terms of Compaction Velocity. Mechanika, 2020. 26(1).

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CE COMPLIANCE FOR CRANES: LIFTING ACCESSORIES AND PROTECTIVE DEVICES AND EQUIPMENT

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Abstract: This research aims to describe the CE marking, including the analysis and description of key segments of the directives and standards that are used in the process of crane conformity. In this way, there will be an easier and more concise overview of the essential requirements that lifting accessories and protective devices and equipment of cranes must fulfill, that will help engineers in the process of aligning cranes with the most important requirements, simplifying their inspection, and ensuring a high level of crane safety during use.
Key words: cranes, CE marking, essential requirements

INTRODUCTION

Through legal and other regulations, each country defines safety management goals and alignment with safety standards. Before 1985, standards were very detailed at the product level, written by lawmakers, and the decision-making process and systematization of product requirements, and the development and implementation of technical ideas took a long time. Introducing the "New Approach", European legislators decided only on the essential safety requirements through legislative and recommended EU guidelines, while the creation of technical specifications was left to economic operators [1].

EU legislation is divided into: regulations (REG), directives (DIR), resolutions (RES), commissions (COM), and recommendations (REC), where directives represent the most important legal instruments, along with regulations, strengthening the EU internal market. Within the framework of standards and directives, the mandatory marking of products with the Conformité Européene - CE mark is introduced, which indicates that the product meets the requirements set out in EU directives and will not endanger the health or safety of users. The New Approach aims to protect public objectives related to the safety and health of product users, as well as to draw attention to potential hazards [2]. This increases consumer confidence in new products bearing the CE mark, which will lead to a higher volume of product purchases, as well as more cost-effective development of new products and increased innovation by manufacturers [3].

The subject and objective of the research are reflected in describing the CE marking, but it will also include a regulatory analysis of lifting accessories and protective devices and equipment of cranes.

CE MARKING

In July of 1993 general rules for a single method of CE marking for the directives were established. In the directives adopted before the said decision, the term "CE mark" is replaced by the term "CE marking" (Fig. 1) [4-6].

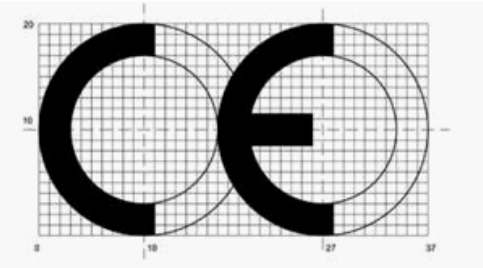


Fig. 1. *"CE marking" defined by 93/465/EEC (source: https://www.paragraf.rs/propisi/t03_0168_s001.gif)*

"CE marking" symbolizes compliance with all obligations of the manufacturer, relating to the product, and the mark is not intended to be used for commercial purposes. Compliance is not limited only to the essential requirements that are related to safety, but also to general health and consumer protection. "CE marking" is the only marking that confirms that products comply with the directives based on a global approach. The CE mark is placed on every product that meets the safety standards that are valid in all EU countries, and it is designed with the intention to facilitate the free movement of goods within the EU [4-6].
Products that don't have a CE mark and that are not in compliance with directives can be restricted for sale or excluded from the European market. If non-conformities are found, or damages or injuries caused by the product occur, the company-manufacturer, or anyone else responsible for selling the product on the European market may bear personal responsibility, that is, they may be prosecuted. The CE mark indicates that the manufacturer has adapted to the requirements of EU legislation and, accordingly, can sell their products freely within the EU, without further modifications or testing. The CE mark is not a quality mark and does not indicate compliance with the standard, but compliance with the legal essential requirements of the EU directives [4-6].
Before placing the product on the market and putting it into operation, the manufacturer must place the CE mark on the product, unless other directives require otherwise. The obligation to place the CE mark applies to all products covered by the directives, which are intended for the EU, including the following products:

- to all new products, manufactured in EU member states or third countries,
- on all used products imported from third countries,
- substantially modified products, which are subject to the directives as new products.

Until the conformity assessment procedure is completed, the CE mark cannot be affixed. This is done to ensure that the product is in compliance with all provisions of the relevant directives. CE marking is usually done at the end of the production phase [4].
The CE mark is placed by the manufacturer or an authorized EU representative, directly on the product or on the data plate, although it can also be placed on the packaging or accompanying documentation. When installing, it is necessary to fulfill the requirement for visibility, that is, that it is easily accessible, legible, and indelible, so that it cannot be removed under normal circumstances without leaving visible traces. The minimum height of the sign should be 5 mm [4-6].
The CE mark can be placed at any other stage of production if it is an inseparable part of the product or its component and if this is justified due to technical or other reasons (for example, the impossibility of meeting the minimum dimensions of the CE mark). In such cases and if the mark is placed on the packaging or accompanying documents, the manufacturer or the authorized body must equally verify the conformity of the product in the production control phase. It is forbidden to omit the CE mark from the product, or to move it to the packaging and

accompanying documentation for aesthetic reasons. Depending on the applied conformity assessment procedures, the authorized body may be involved in the design phase, the production phase or in both phases, and the identification number of the authorized body will follow after the CE mark, if the authorized body is involved in the production phase [4].

REGULATORY ANALYSIS: LIFTING ACCESSORIES AND PROTECTIVE DEVICES AND EQUIPMENT OF CRANES

Šostakov et al. [7] state that safety when working with cranes is achieved through the implementation of constructive and exploitation measures that obligate both crane designers and manufacturers (constructive measures), as well as crane users (exploitation measures). Crane elements which are subjected to different requirements include: (1) load – bearing structure, (2) lifting accessories (hooks, ropes and rope slings, chains and chain slings, lifting straps, sheaves, drums, sprockets), (3) drive mechanism, (4) travel mechanism – wheels, (5) braking mechanism, (6) safety devices, (7) cabin, operator station, and control devices, (8) electrical components, (9) hydraulic components, (10) crane runway and standing area, (11) access – climbing the crane and (12) protective devices and equipment.
The requirements that lifting accessories, protective devices and equipment for cranes must fulfill are based on compliance with various laws, rulebooks, standards, and regulations [8-30]. Reviewing the literature [8-30], a regulatory analysis of lifting accessories and protective devices and equipment of cranes was conducted. The result of a regulatory analysis is shown in Table 1, where the essential requirements that lifting accessories and protective devices and equipment of cranes must fulfill, are explained.

Table 1. *An overview of the essential requirements that lifting accessories and protective devices and equipment of cranes must fulfill*

CRANE ELEMENT	ESSENTIAL REQUIREMENTS
LIFTING ACCESSORIES	
• **HOOKS**	▪ inspected, bearing load capacity mark and attest present, ▪ use exclusively forged or laminated hooks, ▪ manufacturer's marks, serial number, hook number, load capacity, material, and order number must be permanent, ▪ cleaned and maintained, ▪ secure positioning of the load suspension device, ▪ tested with 25% overload, ▪ hook safety latch
• **ROPES AND ROPE SLINGS**	▪ possession of attest, ▪ the rope's construction must correspond to its intended use, ▪ replacement of the rope in cases of wear, abrasion, corrosion, wire breaks, fractures, etc., ▪ fastening means (ferrules, eyes) must have certification and the manufacturer's mark, ▪ regular maintenance, replacement, and inspection, ▪ regular cleaning and lubrication of the rope, ▪ proper storage and handling, ▪ impregnation as protection against rotting, ▪ mandatory inspections and checks
• **CHAINS AND CHAIN SLINGS**	▪ possession of attest, ▪ regular maintenance, inspection, and testing,

	▪ use exclusively of improved chains – LP (heat-treated chains), ▪ possession of the appropriate breaking strength of the chain, ▪ mandatory tag with permanent marking of the chain class, manufacturer, and permitted load, ▪ mandatory use of corner protectors to prevent damage to the load, ▪ chain replacement is necessary in case of length change, wear, damage, or reduction in diameter, ▪ during testing, the chain is loaded with 1.25× the permitted load
• **LIFTING STRAPS**	▪ must have a label with markings of load capacity, length, manufacturer, type, serial number, standard, material, year, and month of production, ▪ the label color must correspond to the type of sling material, ▪ regular inspection, check, and maintenance, ▪ testing is performed once a year, ▪ store on appropriate shelves in a dry area, protected from sunlight, mechanical damage, and chemically aggressive substances
• **SHEAVES, DRUMS, SPROCKETS**	▪ possession of attest, ▪ manufactured in accordance with standards, ▪ sheave rims must be designed to prevent the rope from falling out; drum rims must be high or enclosed in a housing to prevent rope slippage, ▪ grooves must be clean and undamaged, ▪ the rope must be properly wound onto the drum, ▪ a bumper made of elastic material must be installed on the lower sheave assembly to prevent impact when reaching the highest position, ▪ must be withdrawn from use in cases of diameter reduction by a defined percentage or in cases of reduction in groove rim thickness by a defined percentage
PROTECTIVE DEVICES AND EQUIPMENT	
• **PROTECTIVE GUARDS AND PROTECTIVE DEVICES**	▪ robust, securely fastened, must not cause additional hazards, prevent easy dismantling, and bypassing, ▪ installed at an appropriate distance from the danger zone, ▪ designed so that the movement of moving parts and hazardous functions is prevented while within the operator's reach, and the absence of any component should prevent the movement of moving parts or stop them
• **EMERGENCY STOP DEVICE**	▪ clearly recognizable and visible, ▪ quick and unobstructed access, ▪ stops the hazardous operation process as quickly as possible without creating additional risks, ▪ initiates or allows the initiation of certain safety movements,

	▪ once activated, must hold the command until it is explicitly canceled, ▪ shape: red mushroom button on a yellow background
• **SAFETY AND HEALTH SIGNS AT WORK**	▪ installed at the crane's access points, around the crane, and on the crane itself, ▪ all information and warnings must be unambiguous and not overly detailed, ▪ regular maintenance and cleaning, ▪ replacement of worn-out, poorly visible, and unusable signs, ▪ shapes and colors must correspond to their purpose, ▪ pictograms should be as simple and clear as possible, ▪ sign materials must be resistant to impact, water, and other harmful environmental effects, ▪ must be placed in well-lit, accessible, and visible locations

CONCLUSION

The process of harmonizing lifting machines with harmonized standards and all other valid regulations in the given area is a key factor in ensuring the safety of lifting machines. The research showed the essential requirements that lifting accessories and protective devices and equipment of cranes must meet in order to be marked with the CE mark and which is a key indicator of whether the lifting accessories and protective devices and equipment of cranes complies with the relevant technical regulations and directives.
When examining the fundamental requirements, engineers can more effectively match lifting accessories and protective equipment of cranes with CE marking processes, emphasize the crucial safety standards during inspection and testing, and thus enhance the safety of operating cranes.

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REFERENCES

[1] Hanson, J. D. (2005). *CE marking, product standards and world trade*. Edward Elgar Publishing.
[2] Hodges, C. (2001). Safety of consumer products: A new EC directive on the safety of consumer products. European Business Law Review, 274–280.
[3] Twigg-Flesner, C. (2005). Innovation and EU consumer law. Journal of Consumer Policy, 28, 409–342.
[4] Jovišević, V., & Borojević, S. (2010). Standardization and industrial legislation [Script]. Faculty of Mechanical Engineering, Banja Luka.

[5] Hoeven, E. T. (2012). CE-marking: Creating a model for applying the EMC, LVD and machinery directive (Master's thesis). University of Twente.
[6] Huld, P. M. P. (2021). CE marking of a lifting beam (Bachelor thesis). Dalarna University.
[7] Šostakov, R., Zelić, A., & Živanić, D. (2019). Safety and occupational health in the operation of internal transport machinery (Faculty of Technical Sciences). Novi Sad. ISBN: 978-86-6022-155-3.
[8] DIN 15020, Bl. 2:74. (1974). *Hebezeuge – Grundsätze für Seiltriebe. Überwachung im Gebrauch* [Lifting devices – Principles for wire rope drives. Use monitoring].
[9] DIN 3088:76. (1976). *Anschlagseile zum Befestigen von Lasten an Lasthaken* [Lifting ropes for securing loads on hooks].
[10] DIN 61360 T.1:78. (1978). *Hebebänder aus synthetischen Fasern. Begriffe. Maße. Anschlagarten* [Synthetic fiber lifting slings. Terms. Dimensions. Types].
[11] EN ISO 9927-1:2009. (2009). *Cranes — Inspections — Part 1: General*.
[12] SRPS C.H1.306:82. (1982). *Steel wire rope thimbles: Shape and dimensions*.
[13] SRPS C.H1.020:82. (1982). *Steel wire ropes: Types and terms*.
[14] SRPS C.H1.200:81. (1981). *Steel wire ropes: Splicing of wire rope ends*.
[15] SRPS C.H1.300:75. (1975). *Clamps for steel wire ropes for light-duty conditions*.
[16] SRPS C.H1.301:75. (1975). *Clamps for steel wire ropes for heavy-duty conditions*.
[17] SRPS C.H1.302:80. (1980). *Light, medium, and heavy thimbles for steel strands, steel, and fiber ropes: Shape and dimensions*.
[18] SRPS C.H1.303:75. (1975). *Conical ferrules for steel wire ropes: Shape and dimensions*.
[19] SRPS C.H1.304:75. (1975). *Sealing of steel wire rope ends with molten metal: Instructions*.
[20] SRPS C.H1.305:87. (1987). *Flat conical ferrules for steel wire ropes: Shape and dimensions*.
[21] SRPS C.H4.006:94. (1994). *Tested round steel chains: Marking and test report*.
[22] SRPS C.H4.007:94. (1994). *Tested round steel chains: Usage*.
[23] SRPS M.D1.140:75. (1975). *Industrial cranes: Forged load hooks; technical conditions for manufacture and delivery*.
[24] SRPS M.D1.153:75. (1975). *Industrial cranes: Lamellar load hooks; technical conditions for manufacture and delivery*.
[25] Pravilnik o bezbednosti mašina [Rulebook on machine safety] (Official Gazette of RS, Nos. 58/2016 and 21/2020).
[26] Pravilnik o obezbeđivanju oznaka za bezbednost i/ili zdravlje na radu [Rulebook on providing safety and/or health signs at work] (Official Gazette of RS, Nos. 95/10 and 108/17).
[27] Pravilnik o preventivnim merama za bezbedan i zdrav rad pri korišćenju opreme za rad [Rulebook on preventive measures for safe and healthy work when using work equipment] (Official Gazette of RS, Nos. 23/09, 123/12, 102/15, and 101/18).
[28] Dević, M. (1985). *Inspections and testing of machines and devices* (Vol. 3). Center for Information and Publicity.
[29] Karaba, I. (1987). *Manual for crane operation and internal transport*. NIRO Occupational Safety.
[30] Petrović, M., & Petrović, M. (1975). *Occupational safety with cranes* (4th ed.). Institute for Occupational Safety Documentation.

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REVIEW AND ANALYSIS OF REGULATIONS REDUCING MACHINERY SAFETY RISKS ON CONSTRUCTION SITES

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Abstract: This paper provides an overview of EU regulations related to machinery safety, with a particular focus on those frequently used in the construction industry. In addition, Croatian regulations governing occupational safety concerning dangerous machinery, in accordance with EU directives, are reviewed. Safety risks associated with the operation of standard construction machinery are identified, and examples of prescribed measures to mitigate these risks are highlighted.
Key words: EU Directive, Regulation (EU)2024/2847, Croatian regulations, construction machinery, risks, safety measures

INTRODUCTION

Numerous hazards are associated with the operation of machinery, representing potential sources of injury or health damage. In construction, machinery constitutes an almost indispensable component of work equipment, and serious injuries can result from several types of machinery. Studying safety risks is essential to determine measures that can either completely eliminate these risks or reduce them to an acceptable level. Many of these measures are mandated through various levels of legal regulation.
A machine's life cycle encompasses the phases of design, manufacturing, procurement, installation, use, maintenance, transfer, dismantling, modification, recycling/disposal, and sometimes also resale, rental, and lending. Therefore, to effectively reduce the risk of accidents through safety measures and the regulations that govern them, all phases and stakeholders involved in the life cycle of hazardous machinery must be considered. Many risks and costs associated with machinery-related accidents can be avoided through proper design, installation, and maintenance [1]. Regulations governing these aspects must be continually updated and improved in accordance with technological advancements and emerging knowledge of potential risks.
In Croatia, occupational safety regulations have been amended several times over the past 30 years, including those relating to the safe operation of machinery. As an EU member, Croatia is obligated to adopt all directives and regulations mandated by the Union. The new EU Machinery Regulation, which is scheduled to enter into force soon, requires a reassessment of high-risk machinery and the implementation of updated safety requirements [2]. This is particularly relevant for manufacturers, who will be required to design new machines with consideration for the risks associated with emerging technologies.

DEVELOPMENT OF EU REGULATIONS FOR THE SAFE OPERATION OF MACHINERY

In the EU, a machine is considered safe when it complies with all the technical and safety requirements specified in the relevant directives [1, 3]. Directives are legal acts based on Article 100 of the Treaty establishing the European Economic Community, requiring all member states to transpose them into their national legislation within a specified timeframe. The Framework Directive on Safety and Health at Work (Directive 89/391/EEC) and the first Machinery Directive (Directive 89/392/EEC) were both adopted in 1989. Directive 89/391/ECC is known as the social directive because it defines the minimum health and safety requirements that employers must ensure for their employees [3]. Directive 89/392/EEC introduced the obligation for machines to bear the "CE" marking, which must be clearly visible, legible, and

indelible. Manufacturers are required to carry out a conformity assessment procedure to affix the "CE" marking on a machine, which confirms that the machine meets the necessary health and safety requirements and, consequently, may be traded and used within the EU market [4].
In the last decade of the 20th century, several more machinery directives were adopted to complement and expand the scope of the first directive. The machinery directives address the design and manufacturing of machines and incorporate economic aspects by defining essential requirements and conditions for placing machines on the market. The current Directive 2006/42/EC, in force since the end of 2009, regulates the harmonisation of the essential health and safety requirements for machinery at the EU level [4]. It requires machinery manufacturers to identify all potential hazards and conduct a risk assessment addressing injuries and damage caused by machinery. Designers are required to eliminate hazards through safe machine construction or, where elimination is not feasible, to reduce risks to an acceptable level through appropriate measures [5, 6].
In addition to the Machinery Directive, machinery manufacturers must also comply with requirements set by the Pressure Equipment Directive 97/23/EC, the Electromagnetic Compatibility Directive 2004/108/EC, and the Low Voltage Directive 2006/95/EC.
Due to significant technological advancements over the past decade and an evaluation of the effectiveness of the current directive, which revealed certain shortcomings, the European Parliament and the Council published Regulation (EU) 2023/1230 in 2023, intended to replace it. The new Regulation revises the previous directive, although much of its content remains similar or identical. This Regulation has a 42-month transition period and will become fully applicable on January 20, 2027. However, several of its articles, including Article 6 – which allows for the amendment and supplementation of the list of dangerous machinery in Annex I – have already entered into force [2]. Unlike directives, EU regulations are directly applicable in their entirety across all Member States as soon as they enter into force, without the need for transposition into national legislation.
The main objectives of the Machinery Regulation are:

- To better address risks arising from digital and emerging technologies placed on the market, such as artificial intelligence, the Internet of Things, remotely controlled machines, collaborative robotics, etc.;
- To ensure IT security (secure connections between control systems and control networks);
- To check and update the current list of high-risk machines;
- To introduce new requirements for high-risk machinery, requiring enhanced assessment, monitoring, and control to ensure user safety;
- To eliminate interpretative ambiguities.

The Machinery Regulation defines a machine as "an assembly, fitted with or intended to be fitted with a drive system other than directly applied human or animal effort, consisting of linked parts or components, at least one of which moves, and which are joined together for a specific application [2]". A machine is also considered to be an assembly that, while missing only the components to connect it on site or to sources of energy and motion, as well as an assembly that is ready to be installed and able to function as it stands only if mounted on a means of transport, or installed in a building or a structure. Furthermore, a machine is defined as an assembly of linked parts or components, at least one of which moves, and is joined together, intended for lifting loads and whose only power source is directly applied human effort [2].
In addition to machines, the provisions of the new Regulation also apply to interchangeable equipment, such as that commonly used in construction machinery for lifting, load transfer, and earthmoving operations. The Regulation also covers removable mechanical transmission devices, safety components – including load and movement control devices, emergency stop systems, and restraint mechanisms for operators – along with software and digital components providing safety functions. Furthermore, lifting accessories such as chains, ropes, and webbing are included within its scope. For the application of this Regulation, the scope of application of the machine is an important factor, specifically that the machinery is intended for industrial use rather than for household purposes. Article 2 of the Regulation lists 23 types of products –

including equipment, machines, devices, and components – to which its provisions do not apply. Accordingly, the new Regulation, like the previous Directive, applies to the main construction machinery, such as various types of machines for earthmoving and concrete work, various types of cranes, and similar equipment. It is important to note that the Regulation applies only to machines placed on the EU market. Consequently, it applies to machines manufactured outside the EU but imported into the EU market, while it does not apply to machines manufactured within the EU that are intended for sale outside the EU.
Both the current Directive and the new Regulation require manufacturers to prepare appropriate technical documentation and to ensure that machines are accompanied by instructions for use and relevant information and warnings. Annex IV of the Regulation specifies the minimum content of the technical documentation. Crucially, the technical documentation must include risk assessment documentation. This report must include the procedures carried out during the design and manufacturing process, comprising a list of essential health and safety requirements applicable to the machine, a description of the protective measures implemented to meet those requirements, and a description of any residual risks associated with the machine, if present. Additionally, it should document the results of investigations and testing of components, fittings, or the machine itself, conducted by the manufacturer to ensure that the machine has been designed and constructed in such a way that allows it to be safely assembled and put into operation. The information and warnings on the machine should be presented using easily understandable symbols or pictograms, while any accompanying text should be clear and concise. Annex III. of the Regulation specifies the minimum content that instructions must include. Importantly, when machines are imported from other countries into the EU market, the responsibility for providing the instructions and technical documentation that accompany the machines lies with the importers [2].
The new Regulation explicitly allows instructions to be provided in a digital format [2], which offers benefits such as reduced costs associated with paper documentation and improved environmental sustainability. In relation to this, the Regulations set specific obligations for manufacturers when instructions are provided digitally, such as accessibility, the ability to print and download the instructions, and the duration of their availability [7].
Manufacturers generally carry out internal production control (self-certification) [7]. Figure 1 illustrates the sequence of internal production control procedures for machinery, in accordance with Annex VI of the Regulation.

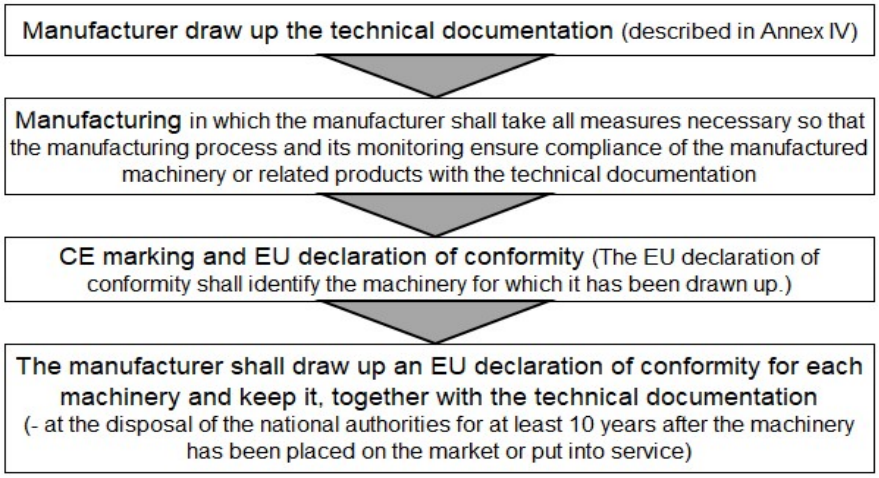


Fig. 1. *Internal control procedures according to Regulation (EU)2023/1230*

Annex I of the new Regulation contains a list of machines that present a higher level of risk and require a special conformity assessment procedure, i.e. certification involving a notified body. Of the machinery used in construction, this mostly concerns sawing and woodworking machinery and devices for the lifting of persons or of persons and goods (if involving a hazard of falling from a vertical height of more than 3 m). The list of machines in Annex I is divided into Part A and Part B. For machines listed in Part A, the conformity assessment must be

conducted by a notified body. Unlike the current Machinery Directive, manufacturers are no longer permitted to self-declare conformity, even if the relevant standards are fully met. Depending on the case, the second, the third, or the fourth conformity assessment procedure must be applied, as briefly outlined in Table 1. For machines listed in Part B of the list, two possible scenarios exist. If the manufacturer designs and constructs the machine in accordance with harmonised standards or common specifications specific to that category, covering all relevant health and safety requirements, the internal production control procedure may be applied. Otherwise, conformity assessment must be conducted by a notified body according to one of the three procedures applicable to Part A machines.

Table 1. *Types of conformity assessment procedures provided for by EU regulation for manufacturers or importers of machinery*

1) Internal control	2) EU type-examination	3) Full quality assurance	4) Conformity based on unit verification
It includes verifying compliance with the essential requirements for a given machine, a process most commonly undertaken by manufacturers or importers, as explained in more detail in Annexes VI and VIII of the Regulation.	For a machine to obtain the CE certificate, the manufacturer is required to carry out specialised testing through a notified body, as explained in more detail in Annex VII of the Regulation.	The procedure requires the manufacturer to obtain a certificate from a body authorized to assess the fundamental quality management system – covering design, production, final inspection, and testing of the machine – before commencing production, as explained in more detail in Annex IX of the Regulation.	This procedure applies to unique machines or related products that are not mass-produced. It is a novelty of the Regulation and is explained in Annex X.

Manufacturers of "smart", connected machines – those directly or indirectly linked to other devices or networks – must also comply with the requirements of Regulation (EU) 2024/2847 (Cyber Resilience Act), which entered into force at the end of last year. This regulation mandates that manufacturers and traders ensure cybersecurity of products with digital components throughout their entire life cycle, including maintenance. Automated and digital solutions on construction machines are increasingly relevant, especially when it comes to dangerous and demanding working conditions [8, 9], and the importance of these requirements in construction practices is expected to grow significantly in the near future.

ALIGNMENT OF CROATIAN LEGISLATION WITH EU REGULATIONS

The first Occupational Safety and Health Act in the Republic of Croatia was passed in 1996, and until the new regulations were passed, those from the Socialist Federal Republic of Yugoslavia were in force. Some of them are still valid, such as the Ordinance on Technical Norms for Cranes, which is important for the safety of machinery.
During Croatia's negotiations for EU accession, efforts were undertaken to harmonize national legislation with EU directives. The current applicable legislation in Croatia is the Occupational Health and Safety Act of 2014, which has been amended in 2014 and 2018. This Act, aligned with existing existing EU regulations, broadly governs occupational health and safety across all sectors. Additionally, a series of ordinances provides more detailed provisions and interpretations for specific areas within the Act. Based on Article 5 of the Act on Technical Requirements for Products and Conformity Assessment (2010), and Article 42, paragraph 2 of the Occupational Health and Safety Act, the Ordinance on Machine Safety and the Ordinance on the Inspection and Testing of Work Equipment were adopted following the entry into force of Directive 2006/42/EC. Directive 2006/42/EC requirements are implemented into Croatian legislation through the Ordinance on Machine Safety, which mandates the assessment of machinery conformity with relevant standards, health, and safety requirements for both placing machinery on the market and its use.

The Ordinance on the Inspection and Testing of Work Equipment regulates periodic inspections and testing but does not intended to compensate for possible non-compliance with the provisions of the Ordinance on the Safety of Machinery when placing them on the market and putting them into use. Its adoption led to the repeal of the previous Ordinance on the List of Machines and Devices with Increased Hazards (2002) and the Ordinance on the Testing of the Work Environment and Machines and Devices with Increased Hazards (2002 and 2003). Consequently, the term "machines and devices with increased hazards", previously listed in the repealed Ordinance, is no longer used in Croatian legislation [11]. However, it is important to note that the list of machines with increased hazards encompasses most machines commonly used on construction sites. The Ordinance on the Inspection and Testing of Work Equipment applies to work equipment that requires handling, control, or servicing by an equipment operator. For example, it does not apply to scaffolding and other equipment used for occasional work at height, which are inspected under separate regulations, nor to handheld mechanized or non-mechanized tools, or to work equipment that only requires start-up and shut-down actions for its intended operation. The scope of this Ordinance includes machines and devices, plants, and load-lifting and transport equipment; thus, standard construction machinery falls within its remit [11, 12].
Inspections and testing are conducted to verify compliance with health and safety requirements for work equipment, aiming to identify and rectify deficiencies that could endanger the safety and health of the operator or other personnel in the vicinity of the equipment's use [11]. An inspection refers to a visual assessment of the functionality of the work equipment, verifying compliance with health and safety requirements according to the manufacturer's technical documentation, confirming the availability of operating instructions, and assessing the maintenance condition of the equipment based on the manufacturer's guidelines or established occupational safety rules. Testing is defined as any other action necessary to determine individual, specific safety and health requirements, carried out using measuring and testing equipment [12]. Table 2 presents the intervals for inspections and testing that employers must ensure for the work equipment they utilize.

Table 2. *Time of mandatory inspections & testing of work equipment according to Croatian regulations*

- Daily visual inspection before using work equipment	
- Within the timeframes specified in the manufacturer's instructions for use and maintenance of the work equipment - Within the period determined by a special regulation	- Before commencing use at a new workplace, if the work equipment has been relocated and subsequently disassembled and reassembled (e.g. tower cranes) - In the event of exceptional circumstances that could threaten the safe operation of the work equipment, such as a change in the mode of operation, damage or defects to the equipment, or worker injuries related to the equipment - Following a decision by the labor inspector - Periodically, at intervals that must not exceed three years

Periodic safety checks of work equipment by authorized personnel do not compensate for non-observance of other prescribed measures. Rather, they serve as audits verifying the employer's fulfillment of obligations under the Occupational Safety and Health Act to ensure that work equipment and personal protective equipment in use are safe, well-maintained, fit for the intended work, and kept in good condition at all times [11, 13].
The Ordinance requires the preparation of a record of completed inspections and tests, and specifies the minimum information that the record must contain [12]. Documents of inspection and testing of work equipment issued in a Member State of the European Economic Area are recognized in Croatia for equipment temporarily used and not assembled at the workplace prior to use, provided these documents are translated into Croatian and written in Latin script, and the inspections and tests are conducted within the prescribed intervals [11].
The regulations emphasize that work equipment should be operated by trained workers, which indicates that training aimed at safe work is expected to lead to the correct use of appropriate personal protective equipment and compliance with the manufacturer's instructions for the equipment. This is expected to significantly reduce potential risks.

RISKS IN THE OPERATION OF CONSTRUCTION MACHINERY AND MEASURES FOR THEIR REDUCTION

Risk assessment increases the safety of machine operators and others potentially harmed by machine failure or unsafe operation. The ISO 12100 standard provides general guidelines for this process. The process of identifying hazards associated with machine operation and assessing the risks of those hazards is demanding for assigning the "CE" marking to the machine. As a first step, the Machinery Directive requires designers and manufacturers to identify hazards that may arise from the use of machinery. This is followed by determining and assessing the risk of accidents, based on the probability and severity of injury or health damage that may result from all foreseeable hazards during the machine's lifecycle, as understood at the time the machine is placed on the market [2, 5]. For machines placed on the EU market, residual risk should be reduced to at least an acceptable level through appropriate design and manufacturing. To achieve this, various safety components are used (such as those presented in Chapter 2), and manufacturers provide instructions for safe use. Annex III of the Regulation enumerates hazards that different machines may present, along with the corresponding measures manufacturers are obliged to implement to minimize these risks. Table 3 details the risks associated with operating the most common types of machinery on construction sites and the prescribed measures for their reduction.

Table 3. *Safety risks when operating standard construction machinery (earthmoving, concrete, and lifting machines) and appropriate manufacturer measures for their reduction (according to [2])*

Safety risks	Prescribed safety measures by machinery manufacturers
Risks of rupture during operation	The instructions for use shall specify the types and frequencies of inspections and maintenance operations required. Where applicable, they must also identify components subject to wear, along with the criteria for their replacement.
Risks related to moving parts of the machine	The machine's moving parts must be designed to prevent any risk of contact that could lead to accidents. If such risks are still present, appropriate guards or protective devices must be installed. Adjustment and maintenance points should be located outside hazardous zones, and tasks such as adjustment, maintenance, repair, cleaning, and servicing should be feasible when the machine is stationary.
Risks of slipping, tripping, or falling	Parts of the machinery intended for movement or standing by persons must be designed and constructed to prevent slipping, tripping, or falling. Where necessary, these parts should be equipped with appropriate handholds. Additionally, any residual risks must be clearly communicated through required warnings.
Risks due to machine movement	Visibility from the driver's (operator's) position must ensure that the machine and its tools can be operated completely safely under reasonably foreseeable conditions of use. Where direct visibility is inadequate, appropriate devices must be provided to eliminate associated risks. If possible, without increasing hazards, a cab should be installed at the driver's (operator's) position, which must include a designated place for the appropriate operating instructions. The movement of a self-propelled machine must only be possible when the driver/operator is at the control device. If there is a risk that operators or other persons being transported on the machine could be crushed between parts of the machine and its surroundings in the event of a rollover or tip-over, the machines must be equipped with a system that keeps persons in their seats or within the protective structure, while allowing necessary movements for work. A visual and audible signal must be provided at the driver's position to warn the driver when the seat belt is not in use. If there is a risk of overturning or tipping of self-propelled machines, or a risk of objects or materials falling onto the machines, they must be equipped with appropriate protective structures. If the machine is equipped with devices extending beyond its movement envelope (such as stabilizers or crane arms), the driver or operator must be able to easily verify before movement that these devices are safely positioned. Mobile machines of greater height (e.g. cranes) must be designed and equipped to prevent the risk of possible contact with overhead power lines or other objects.
Risks associated with lifting machinery	To avoid potential collisions with persons, equipment, or other machines, the control position on the machine must be positioned to provide the broadest possible visibility of the paths of moving parts. Machines must be designed to eliminate the risk of loads falling from their carriers. Machinery with a max. working load $\geq$ 1 t or a maximum overturning moment $\geq$ 40,000 Nm must be equipped with devices to warn the operator and prevent hazardous movements in the event of overloading or exceeding the overturning moment.

	Lifting accessories and their components must have a specified number of permitted uses, and each individual part of a chain, rope, or webbing sling that is not part of an assembly must be marked with its maximum load capacity. The working coefficient (safety factor) of lifting chains must comply with the appropriate safety level, typically with a value of 4.
Risks related to pedestrian-controlled moving machinery	The movement of pedestrian-controlled self-propelled machinery shall only be possible if the operator is continuously engaging the appropriate control device.
Risk of vibrations	Machines must be designed to minimize risks arising from the vibrations they generate, reducing these to the lowest possible level (e.g. the seat must be designed in such a way that vibrations transmitted to the operator are reduced to the lowest possible level), preferably at the source of the risk.
Risk of noise	Machines must be designed to ensure that risks arising from airborne noise emissions are reduced to the lowest possible level, preferably by addressing the source of the noise.
Risk of lightning strike	Machines requiring protection from the lightning effects during operation must be equipped with a system designed to safely conduct the resulting electrical charge to the ground.
Risk of static electricity	Machines must be designed to prevent or limit the accumulation of potentially hazardous electrostatic charges and, where necessary, be equipped with a system for safe discharge of such charges.
Risk of fire	Machines must be designed to eliminate any risk of fire or overheating. In addition, they should incorporate designated locations for the installation of fire extinguishers or be equipped with built-in fire suppression systems.

Regulation (EU) 2023/1230 stipulates that, under the intended conditions of machine use, discomfort, fatigue, and the physical and mental limitations of the operator must be eliminated or reduced to a minimum, considering ergonomic principles. This includes avoiding demanding working postures or movements and manual efforts that exceed the operator's capacity [7]. The elimination or reduction of risk must be the first solution, meaning that technological and organizational measures take priority over measures related to workers' behavior [6]. Employers (construction contractors) are not required to duplicate the risk assessment conducted by the manufacturer in accordance with the Directive. Still, they must identify the residual risk associated with using the machines they operate. Even when machines comply with EU regulations, it is usually necessary to define and implement appropriate measures to reduce any remaining hazards. Residual risk mitigation involves not only timely inspection and proper maintenance of work equipment, but also effective planning and coordination of occupational safety measures at the construction site, effective communication and instruction of workers, worker training, and the use of necessary personal protective equipment [6].

CONCLUSION

With the advancement of technology and the evolving understanding of safety risks, regulations concerning the safe operation of machinery are continuously developing. The transition to the new regulatory framework presents challenges for stakeholders throughout the machine lifecycle, requiring adaptation of practices and ensuring compliance with updated requirements. To facilitate implementation and maintain high safety standards, the literature emphasizes the importance of adequate training and effective communication [14].
The new EU Regulation is primarily important for machine manufacturers, as the reduction of injury and damage risks is achieved mainly through the production of safe machinery that incorporates ergonomic principles and appropriate safety components, etc. However, the regulations also impose obligations on employers (construction contractors) to provide safe working conditions for their employees. Therefore, they must ensure the use of machinery that complies with all prescribed requirements. Consequently, companies involved in construction must consider the new Machinery Regulation during risk assessments for all machines purchased or significantly modified after January 20, 2027. Familiarity with the new regulations on the safe operation of machinery is also important for all professionals involved in planning work processes and workplaces, including those responsible for the detailed construction project execution plan, machine installation and maintenance personnel, and occupational

safety coordinators who oversee and coordinate safety measures on construction sites with multiple contractors.
Even when operating machinery that complies with all safety requirements, residual risk must be reduced to an acceptable level through regular inspections and condition testing of the machinery, combined with adherence to occupational safety regulations.

REFERENCES

[1] Kielesińska, A., Safety of imported machines - Selected issues in the context of Polish (UE) regulation, System Safety: Human - Technical Facility - Environment, Vol.2, No.1., pp. 174–182, 2020.
[2] Regulation (EU) 2023/1230, Official Journal of the European Union, Vol.66, pp. 1–102, 2023.
[3] Kielesińska, A.; Pristavka, M., The machinery safety of management - Selected issues, System Safety: Human - Technical Facility - Environment, Vol.1, No.1., pp. 45–52, 2019.
[4] Lazović, T.; Atanasovska, I., The new machinery regulation (EU) 2023/1230, Proceedings of 8th research-expert conference with international participation "Maintenance 2024 ", pp. 63–70., Zenica, 2024.
[5] Directive 2006/42/EC, Official Journal of the European Union, Vol.39, pp. 1–63, 2006.
[6] Kottelman, M.; Schenk, C.; Pacalova, H.; Bischoff, H.-J.; Drodofsky, S., Majer, I., Sinay, J., Vodič za procjenu rizika u malim i srednjim poduzećima – 2 Opasnosti pri radu sa strojevima i drugom radnom opremom, Verlag Technik & Information e. K., Bochum, 2009.
[7] Begović, V., Novi EU propisi o strojevima, 2023, Available at https://www.sigurnost.eu/novi-eu-propisi-o-strojevima/
[8] Construction by Mineral&Gradnja, Roboti izbušili 9 tisuća rupa tijekom obnove tunela u Njemačkoj, 2025., Available at https://www.construction.hr/novosti
[9] Vidaković, D., Radovanović, Lj., Safety Rules for Working with Tower Cranes, Proceedings of 16th International natural gas, heat and water conference, Osijek, 2025., Article in press
[10] Pravilnik o sigurnosti strojeva, Narodne novine, No.28, 2011.
[11] Internet source: Ministarstvo rada, mirovinskog sustava, obitelji i socijalne politike RH, Primjena odredaba Pravilnika o pregledu i ispitivanju radne opreme, 2019., website: https://uznr.mrms.hr
[12] Pravilnik o pregledu i ispitivanju radne opreme, Narodne novine, No.16, 2016. and No.120, 2022.
[13] Zakon o zaštiti na radu, Narodne novine, No.71, 2014.
[14] Wilkins, J. R., Construction workers' perceptions of health and safety training programmes, Construction Management and Economics, Vol.29, No.10, pp. 1017–1026, 2011.

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ICT APPLICATION FOR PREDICTIVE MAINTENANCE AND LOGISTICS EFFICIENCY IN INDUSTRIAL ENTERPRISES

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Abstract: This paper examines the use of information and communication technologies for predictive maintenance and logistics efficiency in industrial enterprises, with a focus on Serbia. The study discusses digital tools such as sensor networks, IoT systems, predictive analytics, and cloud platforms that support data-driven decision-making. A theoretical model is proposed, consisting of three main elements: ICT infrastructure for predictive maintenance, data-driven logistics systems, and organizational and implementation frameworks. Each element includes sub-elements that explain the connections between data collection, processing, workforce capacity, financial planning, and security. The analysis identifies challenges related to cost, skills, and cybersecurity, while also presenting opportunities through government support, industry collaboration, and scalable technologies. The findings suggest that a structured combination of technological solutions and organizational measures can improve maintenance reliability, logistics transparency, and operational efficiency in industrial enterprises.
Key words: predictive maintenance, logistics, industrial enterprises, ICT application

INTRODUCTION

Information and communication technologies are becoming increasingly present in the management of industrial systems. Predictive maintenance represents one of the most relevant applications, as it allows companies to monitor machinery performance and anticipate failures. Instead of relying only on scheduled inspections or reacting to breakdowns, enterprises can collect continuous streams of data from sensors and diagnostic tools. This information is processed through predictive models that compare current equipment performance with historical patterns. When deviations are detected, the system can suggest intervention before a failure occurs [1]. The same logic applies to logistics operations, where ICT provides tools for integrating multiple activities into a single coherent process. Logistics traditionally includes storage, transport, and distribution, but coordination of these functions is often complex. Digital platforms make it possible to connect suppliers, manufacturers, distributors, and customers in a transparent chain [2]. Tracking systems provide visibility of shipments and allow companies to respond to delays or disruptions with greater accuracy. Route optimization software uses traffic and weather data to recommend more efficient paths for transport vehicles. In warehouses, automated systems supported by ICT improve inventory management and reduce manual errors [3]. The outcome of such integration is a logistics process that uses time and resources more efficiently while meeting customer requirements more consistently.
The use of ICT in industrial enterprises also depends strongly on the ability to generate reliable data. Predictive maintenance cannot function effectively without large datasets describing equipment usage, operating conditions, and past incidents [4]. Similarly, logistics efficiency depends on accurate information about demand, delivery schedules, and transportation capacity. Enterprise resource planning systems combine these streams of

data into centralized platforms, allowing managers to observe key performance indicators in real time. Analytical dashboards help identify trends, forecast demand fluctuations, and make informed decisions. A data-driven approach allows enterprises to align production planning with logistics capacity, which reduces bottlenecks and idle time. In addition, companies can compare current performance with expected benchmarks and adjust operations accordingly [5]. Although the advantages of ICT application are well documented, enterprises often encounter barriers when attempting to adopt such systems. One of the most common obstacles is the high cost of implementation, especially for small and medium-sized firms that operate with limited financial resources [6]. Another challenge is the need for employees to acquire new skills. Maintenance engineers, warehouse staff, and logistics planners may require training to use predictive analytics software and cloud-based platforms. Data security also represents a growing concern, as the exchange of sensitive operational information across networks exposes enterprises to cyber threats [7].

The application of ICT to predictive maintenance and logistics efficiency is closely connected with the broader trends of industrial development. Industry 4.0 is characterized by cyber-physical systems, IoT networks, and data analytics, all of which form the basis for digital transformation in manufacturing and logistics. Enterprises that adopt predictive maintenance are better prepared to achieve continuous production without interruptions, while those that apply ICT to logistics gain more responsive supply chains [8]. These developments show that the integration of ICT into industrial enterprises is not a temporary trend but rather an evolving practice that aligns technical capacity with operational demands.

DIGITAL TOOLS FOR PREDICTIVE MAINTENANCE AND ICT IN LOGISTICS OPERATIONS

Digital tools designed for predictive maintenance are becoming increasingly relevant for industrial enterprises that depend on uninterrupted production. Traditional maintenance strategies often rely on fixed schedules or reactive approaches once failures occur. Such methods can lead to unnecessary costs, since equipment may be serviced too early or too late, and breakdowns may interrupt production. Predictive maintenance supported by ICT addresses these issues through continuous monitoring of machines and equipment. Sensors measure vibration, temperature, pressure, and other variables that indicate the condition of machinery components [9]. The data collected are processed in real time through algorithms that compare current performance with historical records. When patterns deviate from expected conditions, the system signals that maintenance will soon be required. This allows companies to intervene before a breakdown takes place, scheduling service at the most appropriate time.

Predictive maintenance also provides enterprises with more accurate information about the expected lifespan of their equipment. Instead of replacing parts based only on manufacturer guidelines, companies can rely on data that reflect actual operating conditions [10]. This reduces waste and lowers the risk of unnecessary downtime. Maintenance teams can plan their work schedules with more precision, which improves the allocation of human resources. Spare parts can also be ordered in advance, avoiding delays and excess inventory. The adoption of ICT for predictive maintenance therefore contributes to a more organized and cost-effective maintenance process. In addition, detailed historical records of equipment performance help enterprises understand long-term patterns, which informs investment decisions when older machinery needs to be replaced or upgraded.

Another dimension of predictive maintenance is the integration of machine learning models. These models can analyze large datasets from multiple machines simultaneously and detect subtle patterns that human observation would not capture. Over time, the models adapt and improve their predictions, which strengthens the reliability of the system [11]. Enterprises that combine predictive maintenance with such analytical capabilities can reduce both planned and unplanned downtime, improve machine utilization, and manage operational risks more effectively. Although the introduction of these technologies requires investment in equipment

and training, the long-term savings and increased reliability of production make predictive maintenance an attractive option for a wide range of industries.

While predictive maintenance focuses on equipment, ICT also brings extensive opportunities for improving logistics operations. Logistics involves the movement of materials, products, and information across different stages of production and distribution. Inefficiencies in logistics can create delays, raise costs, and reduce customer satisfaction [12]. ICT applications provide solutions to these challenges by integrating the various elements of the logistics process into a coherent system. Transportation management systems, for example, use data about routes, fuel consumption, and delivery schedules to recommend the most efficient allocation of vehicles. Real-time tracking allows enterprises to follow shipments as they move through the supply chain, providing visibility that supports better coordination.

Warehouse operations also benefit significantly from ICT integration. Automated systems supported by barcode scanning, RFID technology, and warehouse management software reduce the possibility of human error in inventory control [13]. Data from these systems indicate which products need to be restocked and where bottlenecks in storage occur. ICT tools can also analyze order patterns and propose adjustments to warehouse layouts to improve efficiency. In combination with predictive analytics, these systems support just-in-time deliveries and help enterprises avoid both overstocking and shortages [14]. The overall effect is a logistics process that uses fewer resources to achieve more reliable outcomes.

The integration of ICT in logistics further extends to collaboration across the supply chain. Cloud-based platforms connect suppliers, manufacturers, and distributors, allowing them to share information in real time. This transparency reduces delays caused by miscommunication and supports more effective planning of production and transport activities. In addition, route optimization software uses traffic and environmental data to identify alternatives that reduce transportation costs and delivery times [15, 16]. Such applications become increasingly valuable when dealing with large and complex supply chains that operate across multiple regions.

DATA DRIVEN DECISION-KING AND CHALLENGES OF ICT IMPLEMENTATION

Innovations in gree The introduction of ICT in industrial enterprises has brought increasing attention to the use of data for decision-making. Predictive maintenance and logistics processes both rely on large volumes of structured and unstructured information that must be properly organized and analyzed [17]. Data from sensors, enterprise systems, and external sources are integrated into central platforms such as enterprise resource planning systems. These systems allow managers to observe performance indicators across maintenance, production, and logistics in one environment [18]. The integration of information reduces the likelihood of decisions based only on partial or outdated data. When predictive models process this information, the results provide indications of when interventions are needed in maintenance or when adjustments are required in logistics planning.

The importance of accurate data becomes especially clear when enterprises attempt to align production schedules with transportation capacities. If demand forecasting is inaccurate, companies may produce goods that cannot be delivered on time due to limited logistics resources. ICT applications mitigate this problem by using historical demand data, market trends, and customer orders to generate forecasts with higher precision [19]. Managers can then compare projected demand with available warehouse capacity and transportation assets. This alignment improves operational efficiency and reduces costs associated with excess inventory or underutilized resources. Dashboards and visualization tools are frequently used to present this information in a clear format, allowing decision-makers to identify problems quickly and take corrective action [20].

Another important aspect of data-driven decision-making is the potential to evaluate performance against benchmarks. Enterprises can measure indicators such as equipment uptime, maintenance costs, delivery accuracy, and warehouse efficiency. When deviations from expected benchmarks occur, managers can investigate the causes and implement targeted measures [21]. This process supports continuous improvement and creates a

structured framework for evaluating the effectiveness of predictive maintenance and logistics operations. In addition, the availability of reliable data helps enterprises to comply with reporting requirements and to provide transparent information to stakeholders.

Despite the clear benefits of ICT applications, industrial enterprises encounter several challenges when adopting new technologies. One of the most frequently mentioned obstacles is the cost of investment. Predictive maintenance requires installation of sensors, data storage systems, and analytical software, while logistics efficiency depends on tracking devices, warehouse management systems, and cloud platforms. These costs can be substantial, particularly for small and medium-sized enterprises [22]. Many companies must carefully assess the expected return on investment before committing to large-scale adoption.

Another barrier is the lack of adequate skills among employees. Maintenance engineers and logistics managers who are accustomed to traditional approaches may find it difficult to adapt to data-driven methods. Training programs and professional development initiatives are required to build competence in using ICT tools effectively. In many cases, companies must rely on external consultants or technology providers to support implementation, which can increase costs and prolong the adoption process. Workforce resistance to change is also a factor, as employees may be hesitant to adopt new systems that alter established routines.

Data security and privacy concerns also present significant challenges. Industrial enterprises exchange sensitive operational information across networks, which makes them vulnerable to cyberattacks. Security breaches can disrupt operations and lead to financial losses or reputational damage [23]. Companies adopting ICT must therefore invest in cybersecurity measures, including firewalls, encryption, and monitoring systems. Regular audits and compliance with international standards are also required to reduce risks. These protective measures add to the overall cost and complexity of ICT adoption but are necessary to ensure reliable and safe operation.

Despite these challenges, opportunities for implementing ICT continue to expand. Cloud-based solutions reduce the need for significant upfront investment in infrastructure, since companies can access software and storage through subscription models. This approach allows smaller enterprises to adopt ICT at a manageable cost and scale the systems as their needs grow. Government programs and industry associations also provide incentives, funding, and technical support for digital transformation projects. Such initiatives create a more favorable environment for enterprises to experiment with predictive maintenance and logistics technologies. Based on the analyzed literature a model for improving predictive maintenance and logistics efficiency is developed. The model is presented on Figure 1.

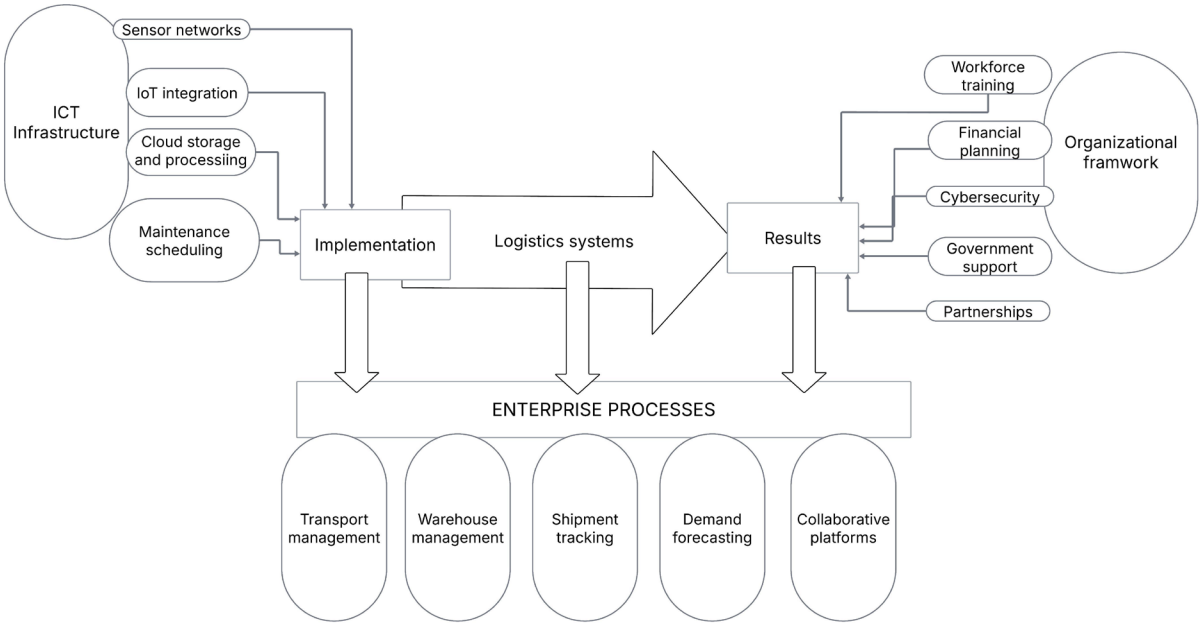


Fig. 1. *Model for improving predictive maintenance and logistics efficiency*

The model shows relations between three main elements and their sub-elements in a structured way. ICT infrastructure forms the technical base for predictive maintenance. Sensor networks provide information about equipment condition, while IoT integration connects machines so that data can be exchanged automatically. Predictive analytics processes these data and identifies patterns that may indicate future equipment problems. Cloud storage supports the management of large volumes of information and allows continuous access. Maintenance scheduling then applies the findings of analytics to plan interventions and organize resources. These sub-elements link together and direct outputs into the implementation stage where enterprise processes receive information needed for maintenance decisions.

Logistics systems are the second major component and include several connected functions. Transport management supports decisions about vehicle routes and schedules. Warehouse management improves tracking of goods and inventory flows. Shipment tracking adds visibility to the movement of goods, allowing more accurate monitoring of supply chains. Demand forecasting uses past data and current trends to adjust production and delivery plans. Collaborative platforms connect suppliers, manufacturers, and distributors to reduce delays caused by missing information. All of these sub-elements influence enterprise processes in areas such as transportation, storage, and distribution, creating more efficient flows of materials and products. The organizational framework provides conditions that support predictive maintenance and logistics systems. Workforce training ensures that employees have the skills to use digital tools for analytics, transport, and warehouse management. Financial planning allows companies to gradually introduce ICT solutions and manage costs over time. Cybersecurity protects operational information against risks linked to digital connectivity. Government support creates standards, incentives, and regulations that guide enterprises in adoption. Partnerships with universities and technology providers contribute to knowledge transfer and help enterprises adapt solutions to their specific context. These sub-elements influence the effectiveness and stability of predictive maintenance and logistics activities and help ensure that results are sustainable. The model indicates that ICT infrastructure and organizational framework direct their influence toward implementation, logistics systems, and measurable results. The outputs then connect with enterprise processes such as transport management, warehouse management, shipment tracking, demand forecasting, and collaboration across supply chains. The relations demonstrate that technological measures and organizational arrangements must work together to achieve improvements. Each sub-element contributes through data provision, structured decision support, or the creation of organizational conditions, and together they support predictive maintenance and logistics efficiency in industrial enterprises.

SUGGESTIONS AND GUIDELINES

Based on the developed model presented in Figure 1, and the reviewed literature, the following guidelines and suggestions are proposed to improve predictive maintenance and logistics efficiency in industrial enterprises in Serbia:

- Governments can introduce financial incentives such as tax reliefs or subsidies for enterprises investing in predictive maintenance and logistics ICT systems.
- National institutions can develop standardized frameworks and technical guidelines for predictive maintenance and logistics systems.
- Enterprises should prioritize the installation of sensor networks and IoT systems to collect real-time data on equipment and logistics processes. Companies can adopt cloud-based platforms that allow scalable data storage and processing for both maintenance and logistics.

- Workforce training programs should be introduced within enterprises to prepare employees for using predictive analytics, transport management software, and warehouse management systems.
- Enterprises can establish partnerships with universities and technology providers to gain access to expertise and tailored solutions.
- Governments can invest in nationwide digital infrastructure, such as broadband expansion, to support ICT adoption in all regions.
- Enterprises should gradually implement cybersecurity measures such as encryption, monitoring systems, and regular audits.
- Individuals working in industrial enterprises can engage in continuous learning through workshops, certifications, and online courses.
- Industry associations can coordinate pilot projects that demonstrate the benefits of predictive maintenance and ICT-based logistics systems.

CONCLUSION

The analysis of predictive maintenance and logistics efficiency in industrial enterprises demonstrates that ICT provides practical solutions for reducing downtime, optimizing resources, and improving decision-making processes. Predictive maintenance supported by sensor networks, IoT integration, and analytics allows equipment monitoring to move from reactive to data-driven approaches. The model developed connects ICT infrastructure, data-driven logistics, and organizational frameworks as the main elements required for improvement. Each element consists of sub-elements that build a structured pathway for enterprises to adopt modern practices. Data integration, financial planning, training, and cybersecurity represent the foundations for long-term success. When these elements are aligned, enterprises are better positioned to manage maintenance and logistics in an efficient and systematic manner.

The findings also highlight that challenges remain in terms of high initial costs, skills gaps, and data security. These barriers are particularly visible among small and medium-sized enterprises in Serbia, where resources are limited. Government support, academic partnerships, and gradual adoption strategies represent ways to address these issues. The combined efforts of institutions, enterprises, and individuals are required to build sustainable systems that rely on ICT for predictive maintenance and logistics efficiency.

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REFERENCES

[1] Jahangir, M. H Sahba, R., Radfar, R., Ghatari, A. R., & Ebrahimi, A. P., Development of Industry 4.0 predictive maintenance architecture for broadcasting chain. Advanced Engineering Informatics, 49, 101324, 2021. https://doi.org/10.1016/j.aei.2021.101324

[2] Aikor, T. S., Transforming logistics management: The role, challenges and opportunities of ICT integration. International Journal of Economics and Management Systems, 10, 2025.

[3] Tukamuhabwa, B., Mutebi, H., & Kyomuhendo, R., Competitive advantage in SMEs: Effect of supply chain management practices, logistics capabilities and logistics integration in a developing country. Journal of Business and Socio-Economic Development, 3(4), 353–371, 2023. https://doi.org/10.1108/JBSED-04-2021-0051

[4] Dachepalli, V., AI-driven decision support systems in ERP. International Journal of Computer Science and Data Engineering, 2(2), 2025. http://dx.doi.org/10.55124/csdb.v2i2.248
[5] Jawad, Z. N., & Balázs, V., Machine learning-driven optimization of enterprise resource planning (ERP) systems: A comprehensive review. Beni-Suef University Journal of Basic and Applied Sciences, 13(1), 4, 2024. https://doi.org/10.1186/s43088-023-00460-y
[6] Skoumpopoulou, D., Toliyat, S. M. H., Ojra, A., Shokri, A., & Hu, S., Challenges of achieving digital transformation in manufacturing firms: The case of predictive maintenance and spare part inventory management. Journal of Manufacturing Technology Management, 36(1), 159–178, 2025. https://doi.org/10.1108/JMTM-04-2024-0211
[7] Molęda, M., Małysiak-Mrozek, B., Ding, W., Sunderam, V., & Mrozek, D., From corrective to predictive maintenance—A review of maintenance approaches for the power industry. Sensors, 23(13), 5970, 2023. https://doi.org/10.3390/s23135970
[8] Shamout, M. D., Chaubey, P. K., Agarwal, P., Adwan, I. A., Sharma, A. K., & Yadav, A. S., Role of industrial automation in terms of providing predictive maintenance in the transportation and logistics sector. In 2022 International Interdisciplinary Humanitarian Conference for Sustainability (IIHC) (pp. 1012–1016). IEEE, 2022. https://doi.org/10.1109/IIHC55949.2022.10060193
[9] Pech, M., Vrchota, J., & Bednář, J., Predictive maintenance and intelligent sensors in smart factory. Sensors, 21(4), 1470, 2021. https://doi.org/10.3390/s21041470
[10] Filz, M. A., Langner, J. E. B., Herrmann, C., & Thiede, S., Data-driven failure mode and effect analysis (FMEA) to enhance maintenance planning. Computers in Industry, 129, 103451, 2021. https://doi.org/10.1016/j.compind.2021.103451
[11] Abidi, M. H., Mohammed, M. K., & Alkhalefah, H., Predictive maintenance planning for Industry 4.0 using machine learning for sustainable manufacturing. Sustainability, 14(6), 3387, 2022. https://doi.org/10.3390/su14063387
[12] Burinskienė, A., The role of ICT in transport and logistics processes management. Entrepreneurship and Sustainability Issues, 11(1), 251–267, 2023. https://doi.org/10.9770/jesi.2023.11.1(15)
[13] Khan, M. G., Huda, N. U., & Zaman, U. K. U., Smart warehouse management system: Architecture, real-time implementation and prototype design. Machines, 10(2), 150, 2022. https://doi.org/10.3390/machines10020150
[14] Mashayekhy, Y., Babaei, A., Yuan, X. M., & Xue, A., Impact of Internet of Things (IoT) on inventory management: A literature survey. Logistics, 6(2), 33, 2022. https://doi.org/10.3390/logistics6020033
[15] Ivanov, D., Dolgui, A., & Sokolov, B., Cloud supply chain: Integrating Industry 4.0 and digital platforms in the "Supply Chain-as-a-Service". Transportation Research Part E: Logistics and Transportation Review, 160, 102676, 2022. https://doi.org/10.1016/j.tre.2022.102676
[16] Chen, W., Men, Y., Fuster, N., Osorio, C., & Juan, A. A., Artificial intelligence in logistics optimization with sustainable criteria: A review. Sustainability, 16(21), 9145, 2024. https://doi.org/10.3390/su16219145
[17] Bousdekis, A., Lepenioti, K., Apostolou, D., & Mentzas, G., A review of data-driven decision-making methods for Industry 4.0 maintenance applications. Electronics, 10(7), 828, 2021. https://doi.org/10.3390/electronics10070828
[18] Perevozova, I., Gubernat, T., Hontar, L., Shayban, V., & Bocharova, N., Using big data analytics to improve logistics processes and forecast demand. Pacific Business Review International, 17(4), 2024.
[19] Punia, S., & Shankar, S., Predictive analytics for demand forecasting: A deep learning-based decision support system. Knowledge-Based Systems, 258, 109956, 2022. https://doi.org/10.1016/j.knosys.2022.109956

[20] Hassankhani Dolatabadi, S., & Budinska, I., Systematic literature review predictive maintenance solutions for SMEs from the last decade. Machines, 9(9), 191, 2021.
[21] Gayialis, S. P., Kechagias, E. P., Konstantakopoulos, G. D., & Papadopoulos, G. A., A predictive maintenance system for reverse supply chain operations. Logistics, 6(1), 4, 2022. https://doi.org/10.3390/logistics6010004
[22] Celestin, M., How predictive maintenance in logistics fleets is reducing equipment downtime and operational losses. Brainae Journal of Business, Sciences and Technology (BJBST), 7(10), 1023–1033, 2023. https://doi.org/10.5281/zenodo.15062856
[23] Hafeez, T., Xu, L., & Mcardle, G., Edge intelligence for data handling and predictive maintenance in IIoT. IEEE Access, 9, 49355–49371, 2021. https://doi.org/10.1109/ACCESS.2021.3069137

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IMPROVING MEASUREMENTS IN AUDIOLOGY USING ELECTROSTATIC TRANSDUCERS

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Abstract: This paper presents a novel approach to refining the parameters of electro-acoustical transducers aimed at achieving the highest quality, most precise sound reproduction, with a primary focus on over ear headphones. It outlines the motivations, objectives, and outcomes of the research dedicated to creating a new type of electrostatic headphone system, usable in measurement systems for audiology applications. Achieving accurate design for electro-acoustic transducers it is crucial to control the frequency, phase, and polar responses of the headphone systems. Most audio devices on the market, even for audiology measurements tend to prioritize frequency response, with varying levels of success. The more linear behavior of the newly developed headphone system is demonstrated through various measurement techniques and listening tests.
Key words: Electro-acoustic sound reproduction, Audiology measurements, DSP processing.

INTRODUCTION

Headphones and transducers play a pivotal role in the field of audiology, serving as the primary interface for sound delivery during diagnostic testing, hearing assessments, and auditory research. Accurate and reliable frequency response is crucial for these applications, as it directly influences the precision of audiometric measurements. Ideally, headphones used in audiology should exhibit a linear frequency response—where each frequency is reproduced at the same level relative to its input—ensuring that sound measurements are consistent and true to the intended signal [1]. However, most commercially available audiometric headphones and transducers suffer from significant nonlinearities in their frequency response, leading to distortion and inaccuracies in the transmitted sound across different frequency ranges [2].
The most commonly used headphones in audiological testing include circumaural and supra-aural models.
Popular examples of circumaural headphones include:
Sennheiser HDA 200 and Telephonics TDH-39, both of which are frequently used in clinical environments due to their durability and broad frequency range in this category [3].

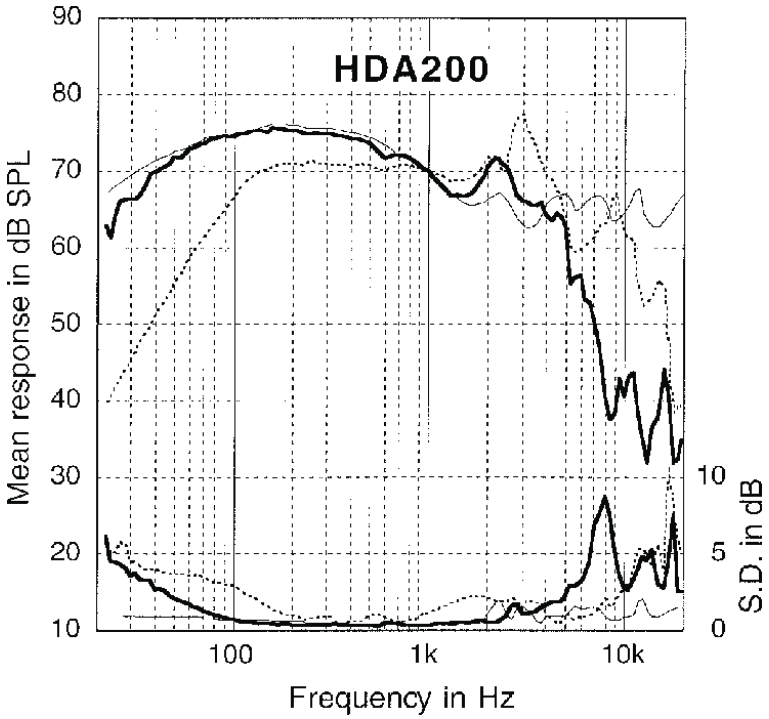


Fig. 1. *Sennheiser HAD 200 Frequency Response [3]*

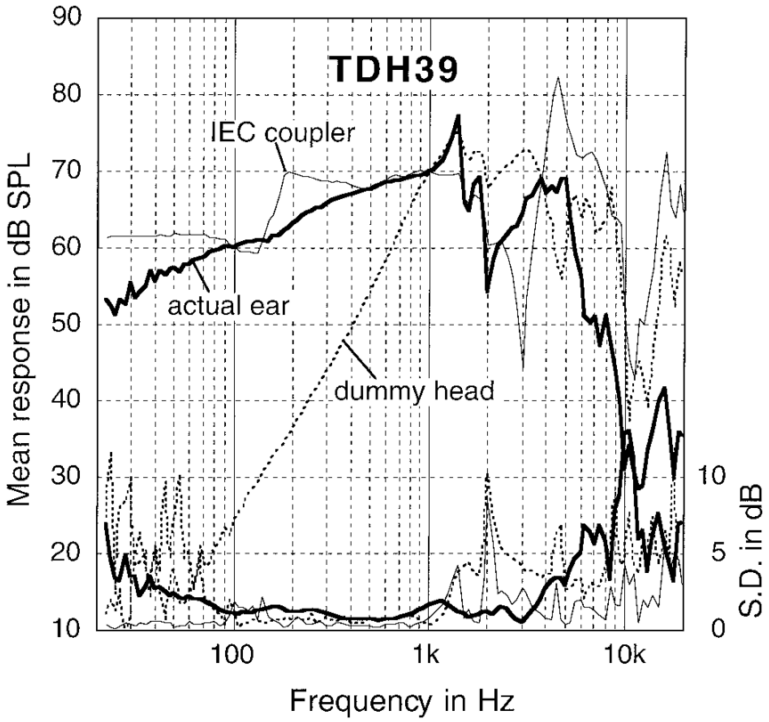


Fig. 2. *Telephonics TDH-39 Frequency Response [3]*

Supra-aural models like the AKG K701, Sennheiser HD 202 and Beyerdynamic DT 770 are also widely utilized for audiometric evaluations, particularly in research settings where precision is paramount. Despite their widespread use, all of these headphones exhibit varying degrees of frequency response nonlinearity, especially at the extreme ends of the frequency spectrum, where inaccuracies become more pronounced [4].

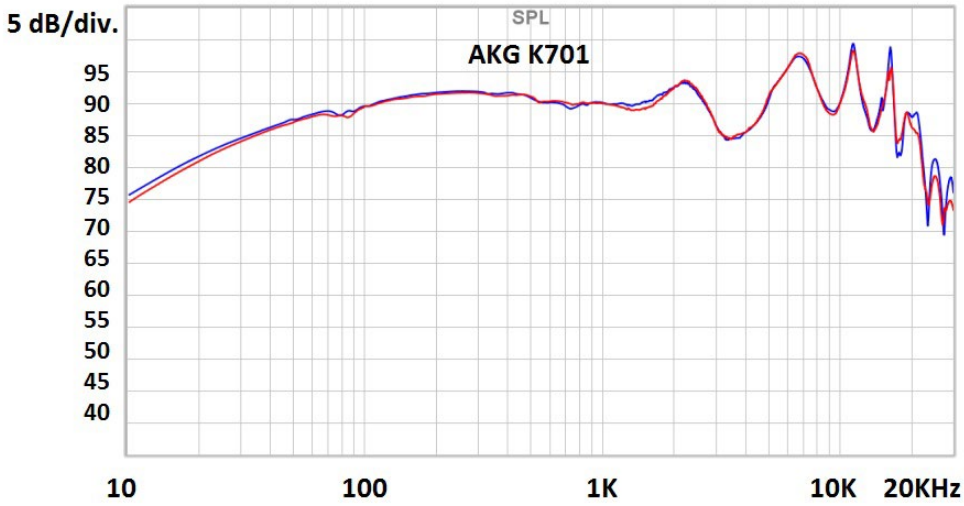


Fig. 3. *AKG K701 Frequency Response [4]*

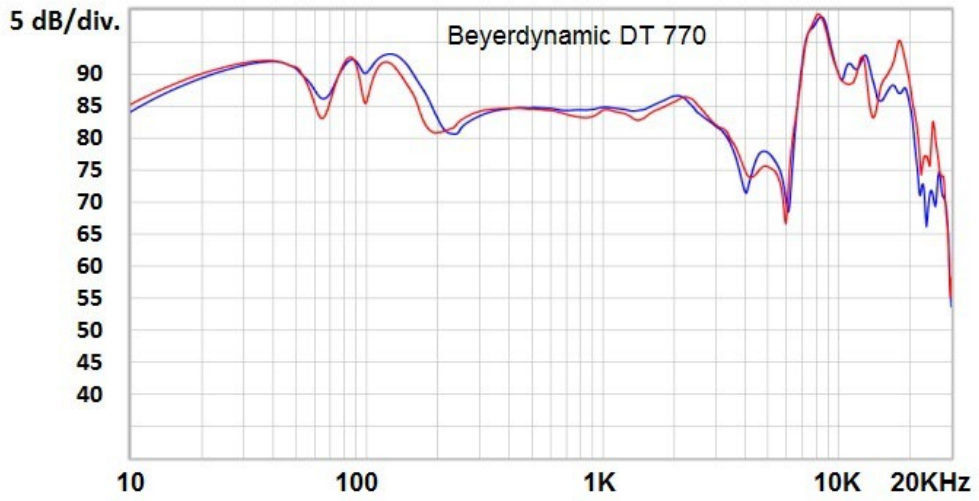


Fig. 4. *Beyerdynamic DT 770 Frequency Response [4]*

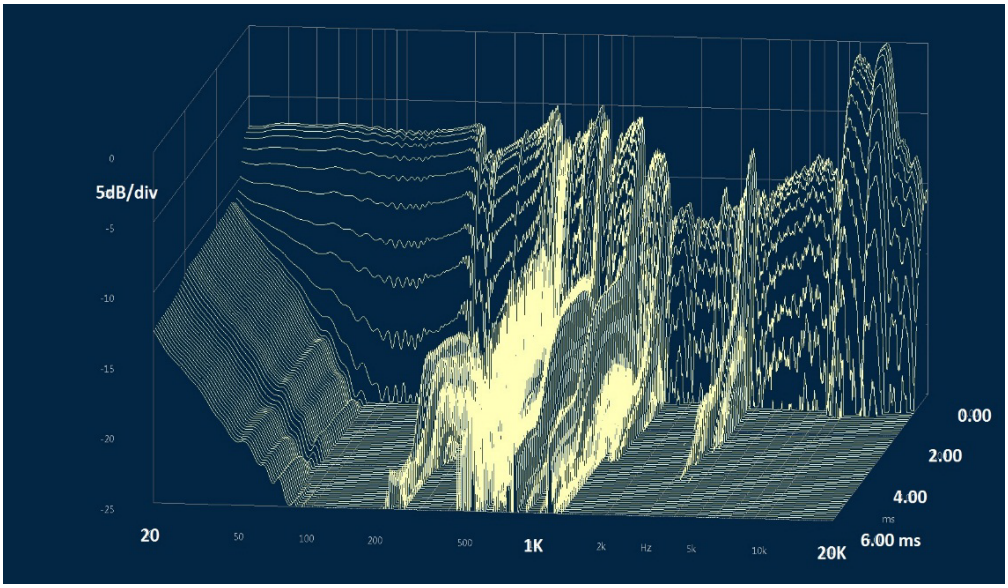


Fig. 5. *Hifiman Susvara Waterfall diagram (Impulse response)*

The challenge posed by these nonlinearities is not merely a matter of poor sound quality, but rather one of compromised measurement precision [5]. In audiological testing, even subtle deviations in the frequency response can lead to skewed thresholds, incorrect diagnosis, and invalid results. To mitigate these issues, modern measurement systems incorporate built-in electronic correction algorithms designed to compensate for the nonlinearity of headphone transducers using DSP processing or software correction methods [6]. These corrections adjust the signals before they reach the headphones, theoretically compensating for any known distortion profiles. However, despite advances in correction technologies, perfect compensation remains elusive, using conventional headphone designs, like Sennheiser HD 202 [7]. The complexity of nonlinearities, especially those introduced by headphone drivers and the coupling with the ear, means that the correction processes can only approximate ideal linearity, and residual errors may still affect the accuracy of the measurement [8].

In this paper, we examine the importance of maintaining a linear frequency response in audiology headphones, explore the inherent nonlinearities present in current headphone models, and evaluate the effectiveness of electronic correction systems in addressing these challenges. Understanding these factors is crucial for improving the precision of auditory measurements and ensuring that the results of audiometric testing are as reliable as possible [9].

MATERIAL AND METHODS

Development Directions

To achieve optimal performance in headphone design, several critical criteria must be met. An electrostatic transducer configuration is preferred, utilizing a membrane with uniform mass distribution and evenly applied tension to eliminate localized resonances caused by structural irregularities. The diaphragm should be sufficiently large relative to the earcup dimensions to support planar wave-front propagation. Additionally, the inner dimensions of the earpads should exceed those of the earcups themselves to prevent mechanical interference or deformation during use. This ensures both consistent acoustic coupling and effective isolation from ambient sound [10].

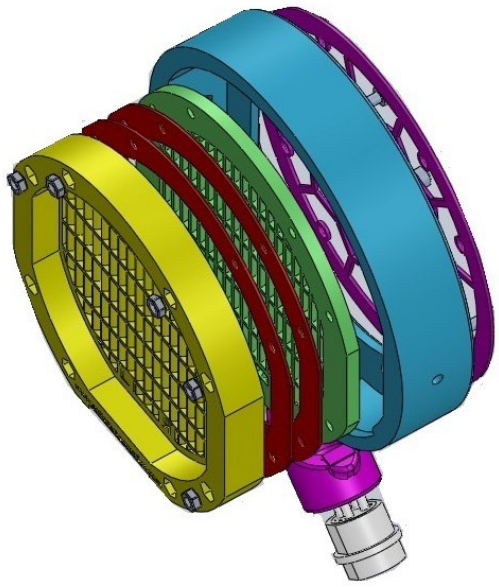


Fig. 6. *Self-Developed Electrostatic Headphone Construction*

Electrostatic transducers offer several key advantages: they facilitate planar wave propagation in both vertical and horizontal axes, exhibit directional (vectored) polar responses within the relevant frequency range, and produce a dipole radiation pattern that helps reduce lateral reflections. Moreover, they are characterized by a highly linear frequency response, minimal distortion, and fast transient response—properties essential for high-fidelity auditory measurements.

Reduced Reliance on DSP Through Improved Headphone Design

In audiological measurements, the accuracy and reliability of test results are heavily dependent on the linearity and consistency of the headphone's acoustic output. Conventional headphone designs often exhibit significant deviations from an ideal frequency response, particularly due to resonances, uneven driver behavior, and imperfect acoustic sealing. These imperfections necessitate complex digital signal processing (DSP) or software-based correction algorithms to compensate for transducer nonlinearities, spatial artifacts, and spectral coloration. While such corrections are essential, they introduce additional layers of signal manipulation that can never fully restore the original signal fidelity, and may even introduce phase errors or latency that affect measurement precision [10].

The implementation of high-performance headphone designs—such as electrostatic transducers with uniform membrane tension, large diaphragms for planar wave generation, and acoustically optimized earcup and earpad geometries—can significantly reduce these inherent acoustic distortions. Such designs naturally provide a flatter frequency response, more consistent polar patterns, and reduced harmonic and intermodulation distortion. As a result, the output signal more closely matches the input without the need for extensive DSP-based equalization or calibration [11].

This enhanced baseline performance reduces the computational burden on measurement systems and minimizes the dependency on correction filters. In practice, this means shorter calibration times, lower signal processing complexity, and fewer error sources in the measurement chain. Ultimately, the use of superior headphone construction contributes to more accurate threshold detection, better reproducibility of audiological tests, and a higher confidence in diagnostic outcomes—especially in clinical environments where precision is critical.

RESULTS AND DISCUSSION

As an initial step, the frequency response measurements are conducted using a semi-dummy head setup. A calibrated measurement condenser microphone is utilized in conjunction with the Audiomatica CLIO (2016) Electrical and Acoustical Measurement System. The procedure is carried out in two phases: first, measurements are taken without the earcup to establish a reference, followed by measurements with a simulated earcup in place to isolate and characterize the acoustic contribution of the earcup itself [12-14].

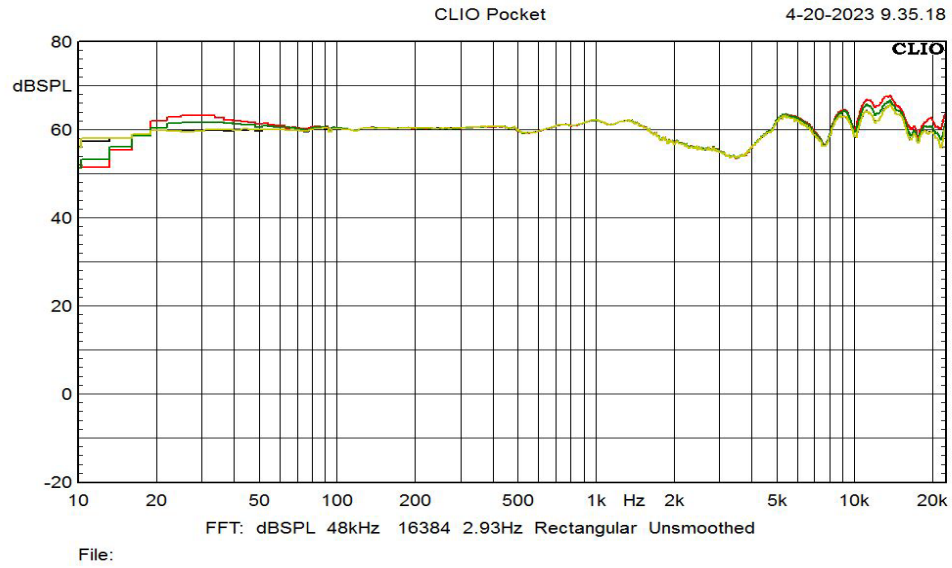


Fig. 7. *Frequency Response of the Self-Developed Electrostatic Headphones with Built-in Frequency Controls [14].*

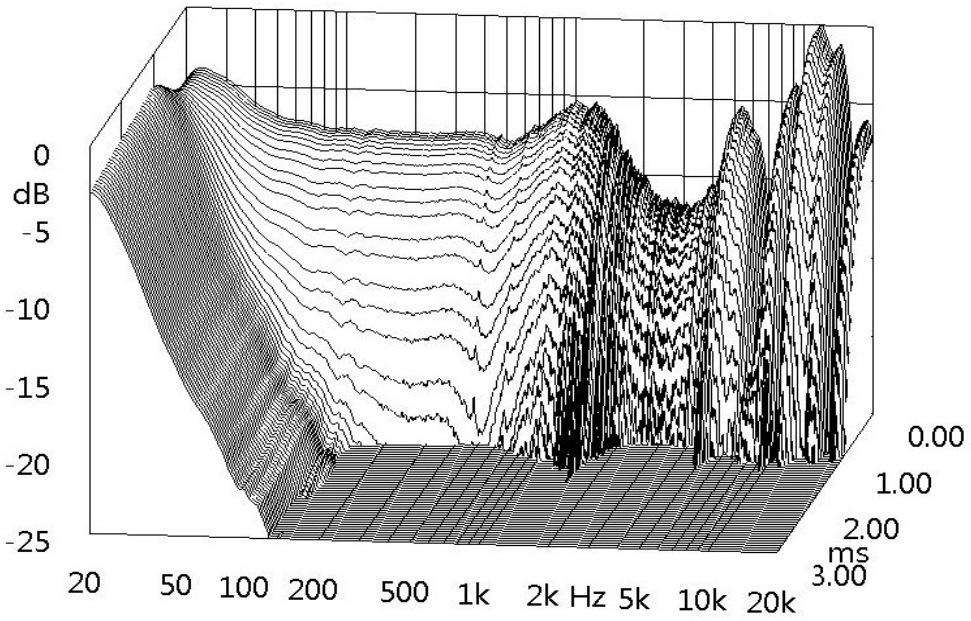


Fig. 8. *Waterfall Diagram of the Self-Developed Electrostatic Headphones [14].*

CONCLUSION

Accurate headphone performance is essential for high-precision audiological measurements, where even minor deviations in frequency response can compromise diagnostic reliability. While traditional headphone designs often require complex digital correction to compensate for acoustic nonlinearities, these corrections are inherently limited and cannot fully restore a linear, phase-coherent response.

This study highlights how advanced headphone construction—particularly electrostatic designs with large, uniform membranes and optimized acoustic coupling—can inherently reduce frequency response irregularities. By minimizing the need for extensive DSP-based compensation, such designs improve measurement accuracy, reduce computational overhead, and enhance repeatability in clinical and research settings.

Ultimately, investing in transducer technologies that prioritize physical linearity over post-processing correction leads to a more robust, reliable foundation for audiological testing, paving the way for improved diagnostic tools and more trustworthy auditory assessments.

REFERENCES

[1] Klinger (1989): Hangdoboz építés, Franzis Kiadó, ISBN: 963-85041 02
[2] Wersényi György (2012): a Pszichoakusztika és az emberi térhallás alapjairól. Alcíme: A 3D akusztikai információ átvitele és feldolgozása, Universitas-Győr, ISBN: 978-963-9819-76-4
[3] Tatsuya Hirahara, Physical characteristics of headphones used in psychophysical experiments, April 2004, Acoustical Science and Technology 25(4):276-285, DOI:10.1250/ast.25.276
[4] Internet source: Diy-Audio-Heaven, headphone measurements, Aviable at: https://diyaudioheaven.wordpress.com/headphones/measurements
[5] Wersényi György (2003): A térbeli hallás BME-TTT
[6] Azza Al-Maskaria, Vinayak Hulihallia, Reza Hoseinabadia, Harvey Dillona,b, Carolyn Meec andKevin J. Munro, Validity and reliability of an automatic audiometry application for iOS iPadswith consumer-grade headphones INTERNATIONAL JOURNAL OF AUDIOLOGY 2025, DOI: 10.1080/14992027.2025.2545439
[7] MeMathieu Van der Aerschot, De Wet Swanepoel, Faheema Mahomed-Asmail, Herman Carel Myburgh, Robert Henry Eikelboom, Affordable headphones for accessible screening audiometry: An evaluation of the Sennheiser HD202 II supra-aural headphone, DOI: 10.1080/14992027.2016.1214756
[8] Kenneth Ooi, Yonggang Xie, Bhan Lam, Woon-Seng Gan, Automation of binaural headphone audio calibration on an artificial head, 2021, DOI: 10.21979/N9/0KYIAU
[9] King Chung, Alternative audiometric calibration methods: Evaluation of sound level measuring apps for audiometric calibration, 2023, DOI: 10.1016/j.jcomdis.2023.106351
[10] Haoran Wang, Yifei Ma, Quincheng Zheng, Ke Cao, Yao Lu, Huikai Xie, Review of Recent Developments of MEMS Speakers, 2021, DOI: 10.3390/mi12101257
[11] Hsin-Yuan Chiang and Yu-Hsi Huang, Experimental modeling and application of push-pull electrostatic speakers, 2019, DOI: 10.1121/1.5130196
[12] Blauert J. (1996): Spatial Hearing: the physics of human sound localization. MIT Press, Cambridge MA ISBN: 9780262024136
[13] Swept Sine Chirps for Measuring Impulse Response (2010): Ian H. Chan, Stanford Research Systems, Inc. 2010 . 1290-D Reamwood Avenue
[14] Audiomatica CLIO (2016) Electrical and Acoustical Measurement System User manual, Release 1.4 Version Pocket

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THE INFLUENCE OF FLUIDS ON THE OPTIMAL OPERATION OF THE HYDRAULIC SYSTEM

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Abstract: This paper indicates the importance of using adequate and high-quality fluid in hydraulic systems. Whether it is simple or more complex systems, the application of the appropriate hydraulic oil plays a decisive role in the optimal functioning of the system. In addition to a quality fluid, there must be a filter in the system, so that the separation of particles from the oil is effective and so that clean oil can circulate through the system again. In some cases, where there are high temperature areas, the installation of an oil cooler is necessary. Also in this work, examples of wear of certain components caused by harmful effects on the fluid, through the oxidation process, will be shown.
Key words: hydraulic systems, fluid.

INTRODUCTION

Hydraulic systems are characterized by the fact that the transmission of energy is carried out by a liquid under a certain pressure. Fluid pressure is evenly distributed on all sides in a closed system. Hydraulic oil is used as the working fluid in hydraulic systems. When it comes to energy transfer, it is necessary to distinguish between hydrostatic and hydrodynamic energy transfer. When the energy acting on the donor cylinder is transferred to the working cylinder by means of a column of liquid, then it is a question of hydrostatic energy transfer, while in hydrodynamic systems the pump produces working pressure which is transferred to the executive components of the system by means of the working fluid (hydraulic oil). These include hydraulic motors and hydraulic cylinders, [6].
The basic function of hydraulic oil is to act as a medium to transmit force from one point to another. In addition, the hydraulic oil must:

- Ensure adequate lubrication,
- Ensure proper sealing,
- Protects the system from rust and corrosion,
- Ensure adequate oil film strength in order to reduce wear,
- Has the ability to quickly settle and separate insoluble particles that enter the system,
- Dissipates heat well,
- It has good viscous-temperature characteristics,
- Compatible with sealing materials,
- It has good oxidation and thermal stability, which ensures a long replacement interval, [6].

The hydraulic fluid belongs to the components of the hydraulic system, in order to be able to fulfill the required functions of the criteria, it must meet the regulations that are defined according to the components of the system itself. At the very beginning of the development of hydraulic systems, the first fluid was water. Its main disadvantage is that it turns into a solid aggregate state at temperatures below 0 °C, forms corrosion on the surface, which indicates a poor lubrication function. After water, emulsions and rapeseed oil were used in hydraulics, but still the problems were not completely solved, but the harmful properties of water as a hydraulic fluid were only mitigated. After refining oil, and obtaining fuel and oil, the use of base oil in hydraulic systems began through the distillation process, [4].
Today there are several types of hydraulic fluids, and they can be divided into:

- Mineral hydraulic oils,
- Synthetic hydraulic oils,
- Plant-based hydraulic oils, [3].

The advantages of mineral oils are reflected in better lubrication ability, protection against corrosion, and can be used in the temperature range from -50 ºC to 80 ºC, and the disadvantages of mineral oils are large changes in viscosity depending on temperature and separation of resin at high temperatures, [1].
Plant-based hydraulic oils are obtained from renewable sources, such as vegetable oils or animal fats. Although they are environmentally acceptable due to their biodegradability, they still do not have good enough characteristics like mineral or synthetic oils. They are used with natural rubber gaskets, [4].
The efficiency of the hydraulic system largely depends on the properties of the working fluid used in the hydraulic system. The choice of an adequate working fluid has an important influence on the functionality, reliability, service life and economy of the hydraulic system, [3].
The tasks of the working fluid are:

- Energy transfer,
- Cooling,
- Lubrication,
- Sealing,
- Corrosion protection,
- Removal of impurities, [1].

CLEANLINESS OF HYDRAULIC OIL

High-quality hydraulic oil is characterized by high oxidation stability and guarantees a long working life of the fluid, it is incompressible, which means that it provides adequate protection against wear, has good temperature-viscosity characteristics, which is very important for mobile systems, quickly and completely separates water and air, protecting the pump from cavitation, has a low tendency to foam, effectively protects against rust and corrosion, is compatible with standard seals and has good filterability, [7].
Depending on the application, hydraulic oil may also be required to:

- Detergent properties,
- Biodegradability,
- Non-flammability,
- High oil purity due to small gaps in the system and the like, [3].

The use of low-quality hydraulic oils causes the appearance of corrosion, wear, oil degradation and the separation of sediment, contamination, filter blocking and valve clogging, and thus there is an increase in production costs caused by equipment damage, oil degradation and the need for premature replacement, the need for more frequent equipment servicing and the replacement of filters and other worn parts of the system, all of which is accompanied by expensive production stoppages, [8].
Regarding the definition of oil purity, there are several standards. The most frequently mentioned are:

- ISO 4406:2021,
- NAS 1638,
- SAE AS4059, [7].

Table 1. *Classification of oil purity by different standards, [7].*

	Standard designation		
	4406:2021	NAS 1638	SAE AS4059
Oil volumes	1ml	100ml	100ml
Recording in:	3 dimensions	2 dimensions	3 dimensions
Solid particle sizes	>4μm >6μm >14μm	5 - 15 μm 15 - 25 μm 25 - 50 μm 50 - 100 μm >100 μm	4 - 6 μm 6 - 14 μm 14 - 21 μm 21 - 38 μm 38 - 70 μm >70 μm
An example of marking oil purity	19/17/14	8	8

PROCESS OF OXIDATION AND WEAR OF HYDRAULIC SYSTEM COMPONENTS

The oxidation process of hydraulic oil changes its properties. This process is accelerated by increased temperature, the presence of air and sunlight. It has the greatest influence on the viscosity of the oil, and can be monitored by the change in color and smell. As a consequence of the content of solid particles in the oil, wear occurs on the surface of the hydraulic system, where a certain number of new particles are created, which causes more intensive wear of the system. In addition, metal particles have a catalytic effect on oil oxidation, [2].



Fig. 1. *Cylinder piston rod exposed to the wear process[7].*

Mixing hydraulic oils is not recommended because hydraulic fluids consist of a base oil that makes up about 90% of the mixture and additives. The base oil can be of different origin, and in order to improve properties such as viscosity, resistance to wear, corrosion, foaming, it is necessary to add different additives to meet the needs of the hydraulic system, [9].
Possible causes of excessive wear of hydraulic system parts are:

- Abrasive substances circulate through the hydraulic oil pump, which means that an appropriate filter should be installed or the oil changed more often,
- Oil viscosity at operating conditions too low,
- Constantly high pressure above the maximum nominal characteristic of the pump, in which case the maximum set value of the safety or control valve should be checked,

- Air in the system worsens lubrication, i.e. increases wear of parts,
- Intensive wear of the sealing plug occurs if the cylinder is not well attached to the frame and vibrates, if the cylinder and connecting rod extension are not adjusted or if there is a large lateral pressure on the connecting rod, [7].

It is generally known that working at high pressures adversely affects the elements of vane pumps, especially when it comes to the stator ring and vanes. At the very beginning of the development of vane pumps, the use of unalloyed oils caused intensive wear of the pump components, and in order to improve the quality of lubrication, additives were added to the oil. Their basic role was to enable work at higher pressures while mitigating the wear process. The additive composition was in most cases based on zinc and phosphorus. The working fluid (oil) has the role of separating the points of contact between the tips of the blades and the surface of the stator. For this purpose, additives intended for operation at high pressure values are added to the oil. However, even the addition of additives did not completely solve the problem of wear of vane pump elements, so the leading pump manufacturers had to work on reducing the load, especially on the contact points in the areas of high mechanical pressure. One of the construction solutions was the production of wings that contain a double contact surface. The availability of newer materials in production has significantly reduced the wear of critical elements of the vane pump, [5].



Fig 2. *Example of vane pump surface wear, [10].*

CONCLUSION

This paper highlights the importance of oil within a hydraulic system. Also, this area indicates the possibility of accelerated development, bearing in mind that at the very beginning of the development of hydraulics, the working fluid was water. After the production of rapeseed oil, oil refining technology contributed to the creation of the fluids we have today. However, some disadvantages still exist due to the different requirements that the working fluid must meet, first of all, work at a wide range of temperature ranges, over the viscosity that should be within the permitted limits in different working conditions, and so on.

REFERENCES

[1] P. Modi, S. Seth, Hydraulics & Fluid Mechanics including Hydraulics Machines, ISBN 978-81-89401-26-9, 2017. ¶ (11 pt.)
[2] M. Khalil, Hydraulic Systems Volume 1 – Introduction to Hydraulics for Industry Professionals, ISBN: 978-0-692-62236-0, 2016.
[3] Vuković V., Introduction to Hydropneumatic Technique, STILOS, Novi Sad 1998.
[4] Adamović, Ž., Radovanović, Lj., Hydraulics and pneumatics, Technical Faculty "Mihajlo Pupin", Zrenjanin, 2005.
[5] Bogdanović B,. Nikodijević D., Vilić A., Hydraulic and hydromechanical power transmissions, Faculty of Mechanical Engineering, Niš, 1999.
[6] Internet source: https://www.nisotec.eu/sr-lat/hidraulicna-ulja

[7] Internet source: https://mhs.rs/jedinstvo-hidraulicnog-sistema-i-ulja-ulje-u-hidraulicnom-sistemu-1-deo/
[8] Internet source: http://www.tritonoil.rs/proizvodi/industrijska-ulja/hidraulicna-ulja/
[9] Internet source: https://www.adeco.rs/savet/43/PROBLEM-MESANJA-RAZLICITIH-HIDRAULICKIH-FLUIDA/
[10] https://mhs.rs/zapreminske-pumpe-mehanizmi-habanja-4-mehanizmi-habanja-krilnih-pumpi/



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IMPACT OF GAS FLARING AND VENTING PROCESSES IN THE OIL INDUSTRY ON AIR QUALITY

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Abstract: This review paper examines the impact of gas flaring and direct venting in the oil and gas industry on air quality and climate change. Flaring generates CO_2, NO_x, SO_2, and fine particulate matter, including black carbon, while venting directly releases methane with a high short-term global warming potential. Due to variable combustion efficiency, unlit flares, and systematic venting, actual emissions often exceed reported inventories. We summarize findings from studies based on satellite assessments and targeted field measurements, including the identification of 'ultra-emitters' and epidemiological evidence of local health effects. Regulatory trends (EU, USA) toward banning routine flaring/venting, introducing mandatory MRV/LDAR programs, and aligning with international initiatives are discussed. Technological mitigation measures are presented (gas capture and reuse, replacement of pneumatic equipment with low-emission alternatives, closed-loop systems, and, where applicable, CCS) along with their medium-term cost-effectiveness. We conclude that the rapid implementation of available solutions is crucial for achieving sustainable development goals, improving air quality, and supporting the energy transition.
Key words: gas flaring; venting; methane; air quality; black carbon; MRV/LDAR; ultra-emitters; energy transition

INTRODUCTION

The oil industry, through its operations of gas flaring and direct venting, represents a significant source of air pollution and greenhouse gas emissions [3, 5]. Gas flaring releases a wide spectrum of pollutants — including CO_2, CO, NO_x, SO_2, volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), and black carbon — which exert local, regional, and global climate effects [1–3, 5]. Venting, on the other hand, releases large quantities of methane — a super greenhouse gas with a substantially higher short-term global warming potential compared to CO_2 [3, 5]. Due to inconsistent reporting and the intermittent nature of these processes, actual emissions are often significantly higher than officially reported [1–5]. The aim of this paper is to provide a concise overview of existing studies on the impact of flaring and venting in the oil industry on air quality, with a particular focus on harmful gas emissions, climate change, and human health. The paper draws upon analyses from the literature that include satellite-based emission assessments, health impacts, and emission reduction methods, with the goal of providing a relevant review for conference presentation [2, 3, 5]. In the context of global climate challenges, particularly within the framework of the Paris Agreement and the 2030 Agenda, methane reduction has emerged as one of the key issues for achieving a sustainable energy transition. Flaring and venting are increasingly viewed not only as technical or safety processes but also as critical factors in climate policy, public health, and sustainable development. Their connection to air quality, regional community health, and global climate effects makes them a topic of particular importance for scientific gatherings and international initiatives. Moreover, the continuous development of satellite technologies and monitoring systems enables more accurate quantification of emissions, thereby narrowing the gap between reported and actual data. This, in turn, provides a foundation for more precise regulations, stronger oversight, and broader implementation of emission reduction measures in the oil and gas sector. The following sections provide a detailed discussion of flaring and venting processes, their environmental and health impacts, as well as possibilities and perspectives for their mitigation.

MATERIAL AND METHODS

This review synthesizes peer-reviewed literature, satellite-based assessments, targeted field measurements, and epidemiological studies, complemented by regulatory and policy documents (EU/US frameworks and UN initiatives). Sources were screened for methodological transparency and relevance to (i) flare efficiency and emissions composition, (ii) methane venting magnitudes, (iii) health impacts, and (iv) mitigation options and costs. Evidence was organized into two process streams—flaring and venting—to enable consistent comparison of emission pathways, measurement approaches, and reported uncertainties. Where available, cross-study contrasts (e.g., aircraft campaigns vs. satellite retrievals) were used to contextualize inventory gaps and to inform the subsequent discussion of technological and regulatory mitigation.

Gas flaring process

Gas flaring is the controlled combustion of excess gas at a flare stack, applied when the gas cannot be captured or utilized due to safety, operational, or infrastructural reasons [1]. Three main types are typically distinguished: emergency flaring during abnormal pressure events, temporary flaring during plant start-ups or shutdowns, and routine flaring where no gas recovery systems are in place [6]. Although the intended outcome of combustion is to convert methane into carbon dioxide, actual efficiency depends on gas composition, flow rate, and atmospheric conditions, and often deviates from the idealized 98% assumed in emission inventories [8]. Major emissions include CO_2 and CO, nitrogen oxides (NO_x), sulfur dioxide (SO_2), volatile organic compounds, and fine particulates, with black carbon being of particular concern [1]. Aircraft-based measurements in the Bakken Basin (North Dakota) revealed that a portion of flares operate with substantially lower efficiency, leading to higher methane and black carbon emissions than predicted by standard factors [7]. An analysis of more than 300 flares in the United States demonstrated that inefficient and unlit flares reduce the effective methane destruction rate to an average of about 91%, significantly increasing its contribution to global warming [8]. Measurements in the North Sea showed a median combustion efficiency of around 98%, but also significant NO_x emissions, confirming that even at high efficiency, pollutants relevant to air quality are generated [6]. The health impact of flaring has also been epidemiologically confirmed: in the Eagle Ford region of Texas, intensive flaring was associated with increased incidence of preterm births [9]. Regional studies in Nigeria demonstrated that meteorological factors and flare characteristics influence the dispersion of CO, SO_2, and black carbon into populated areas, thereby worsening air quality [10]. At the global scale, satellite data (e.g., Sentinel-3A SLSTR) have enabled the quantification of flaring and black carbon emissions, with Russia and the United States identified as the largest contributors [11]. These analyses confirm that flaring remains a significant source of CO_2, NO_x, SO_2, particulates, and methane, with implications for local air pollution episodes and global climate change [1].

Gas venting process

Venting refers to the intentional release of unburned natural gas (predominantly CH_4) into the atmosphere from equipment and processes in the oil and gas industry, typically during testing, maintenance, start-up/shutdown procedures, operation of pneumatic devices, or in the absence of gas handling infrastructure [2]. Unlike flaring, venting does not oxidize methane into CO_2, so its primary climate impact derives from the direct release of CH_4 [2, 12]. In practice, some processes are even designed to periodically or continuously release gas (e.g., tank venting, safety valves), making venting a systematic emission source when gas capture and utilization are absent [12]. Methane has a much stronger warming effect per ton than CO_2; recent radiative forcing calculations have revised upward the impact of CH_4 compared to earlier estimates, which makes the climate consequences of venting proportionally greater [13]. Given methane's relatively short atmospheric lifetime (~12 years), rapid venting reduction

delivers immediate climate benefits and high cost-effectiveness of mitigation measures [14]. In heavy oil recovery operations without combustion (e.g., CHOPS), venting is frequent and often underestimated in inventories [4]. Field measurements at five CHOPS facilities in Alberta revealed large discrepancies between measured and reported rates, identifying venting (particularly 'casing gas') as the dominant source [15]. Broader measurement syntheses in the United States indicate that methane emissions in the production segment are ~1.5–2× higher than official inventories, with a portion of emissions stemming from processes that deliberately vent gas [12]. Satellite analyses also reveal episodes of 'ultra-emitters' in oil and gas basins worldwide (maintenance, malfunctions, venting), which account for a significant share of total emissions and are a target for rapid mitigation [16]. These findings are driving regulatory policies toward 'zero routine venting,' mandatory measurement, and faster source elimination [17]. In 2024, the European Union adopted a methane emissions reduction regulation in the energy sector that bans routine venting/flaring (with safety exceptions) and introduces mandatory MRV and LDAR practices [17, 18]. In addition, UN initiatives (e.g., UNEP OGMP 2.0 and the Global Methane Pledge) encourage companies and governments to transition from estimates to measurements and to reduce intentional venting [19, 20]. Technical measures (gas capture and reuse, replacement of pneumatic devices with low-emission alternatives, compression and closed-loop systems) have been identified as widely available and cost-effective options for rapid venting reduction [12, 14].

RESULTS AND DISCUSSION

Flaring and venting processes involve different mechanisms and environmental consequences, yet both represent significant sources of greenhouse gas emissions [1, 2]. Flaring primarily converts methane into CO_2 but simultaneously produces NO_x, SO_2, and black carbon, contributing to air pollution and short-term climate warming [1, 5, 6]. Venting, by contrast, directly releases methane into the atmosphere, emitting a gas with a substantially higher global warming potential over shorter timescales [2, 12, 13]. The combined effects of these processes are reflected in both local health outcomes and global climate change. Studies in Texas have shown a correlation between intensive flaring and increased risk of preterm births, highlighting the health implications of exposure to a mixture of pollutants [9]. In Canada, measurements at heavy oil production facilities confirmed that venting is frequently underestimated and that actual emissions can be several times higher than reported [4, 15]. At the global level, satellite analyses have identified the occurrence of 'ultra-emitters,' i.e., massive methane release events that significantly contribute to total emissions and demand urgent mitigation measures [16]. Technological options for emission reduction include gas capture and reuse systems, installation of low-emission equipment in place of pneumatic devices, closed-cycle compression systems, and carbon capture and storage (CCS) technologies [12, 14]. According to assessment models, rapid implementation of these measures could substantially reduce global methane emissions by 2050 at relatively low costs [14]. The regulatory framework is becoming increasingly stringent, particularly in the EU and the USA, where routine venting and flaring are prohibited, mandatory monitoring programs and super-emitter detection are introduced, along with international initiatives such as UNEP OGMP 2.0 and the Global Methane Pledge [17–20]. These trends emphasize the transition to sustainable technologies and the growing pressure from international organizations to reduce methane emissions as quickly as possible.

CONCLUSION

Gas flaring and venting in the oil and gas industry are significant sources of air pollution and greenhouse gas emissions. Flaring generates a mixture of CO_2, NO_x, SO_2, and particulates (including black carbon), while venting directly releases methane with a high short-term climate impact [1,2]. Variable combustion efficiency, unlit flares, and systematic venting contribute to actual emissions exceeding reported levels, thereby amplifying both local health risks and global climate impacts [6,8,9,12]. Satellite observations and targeted measurement campaigns

have identified episodes of 'ultra-emitters' and demonstrated that emissions in the production segment are often 1.5–2× higher than inventories, underscoring the need for evidence-based measurements and rapid interventions [12,16]. Reducing emissions requires a combination of technical and regulatory solutions: gas capture and reuse, replacement of pneumatic devices with low-emission alternatives, closed-loop systems, and complementary measures (e.g., CCS where justified), alongside mandatory MRV/LDAR programs and super-emitter detection [12,14]. The new regulatory frameworks in the EU and USA, as well as initiatives such as OGMP 2.0 and the Global Methane Pledge, are steering the sector toward a 'zero routine flaring/venting' regime and more transparent reporting [17–20]. Looking ahead, the rapid implementation of available measures, coupled with stronger oversight and standards, can deliver significant and cost-effective reductions, support sustainable development goals, and accelerate the energy transition, while simultaneously improving air quality and public health [14,17–20]. The key challenge in the coming period will be balancing the economic interests of oil and gas companies with increasingly stringent regulatory requirements. Although technologies capable of substantially reducing emissions are already available, their widespread adoption will depend on political will, financial incentives, and international cooperation. Ultimately, this combination of factors will determine the pace at which the industry transitions to more sustainable practices and contributes to mitigating climate change.

REFERENCES

[1] Fawole, O. G., Cai, X.-M., & MacKenzie, A. R., Gas flaring and resultant air pollution: A review focusing on black carbon, Environmental Pollution, vol. 216, pp. 182–197, 2016. doi:10.1016/j.envpol.2016.05.075

[2] Soltanieh, M., Zohrabian, A., Gholipour, M. J., & Kalnay, E., A review of global gas flaring and venting and impact on the environment: Case study of Iran, International Journal of Greenhouse Gas Control, vol. 49, pp. 488–509, 2016. doi:10.1016/j.ijggc.2016.02.010

[3] Tran, H., Polka, E., Buonocore, J. J., Roy, A., Trask, B., Hull, H., & Arunachalam, S., Air quality and health impacts of onshore oil and gas flaring and venting activities estimated using refined satellite-based emissions, GeoHealth, vol. 8, no. 3, e2023GH000938, 2024. https://doi.org/10.1029/2023GH000938

[4] Festa-Bianchet, S. A., Tyner, D. R., Seymour, S. P., & Johnson, M. R., Methane venting at Cold Heavy Oil Production with Sand (CHOPS) facilities is significantly underreported and led by high-emitting wells with low or negative value, Environmental Science & Technology, vol. 57, no. 8, pp. 3021–3030, 2023. https://doi.org/10.1021/acs.est.2c06255

[5] Chen, C., McCabe, D. C., Fleischman, L. E., & Cohan, D. S., Black carbon emissions and associated health impacts of gas flaring in the United States, Atmosphere, vol. 13, no. 3, 385, 2022. https://doi.org/10.3390/atmos13030385

[6] Shaw, J. T., Foulds, A., Wilde, S., Barker, P., Squires, F. A., Lee, J., Purvis, R., Burton, R., Colfescu, I., Mobbs, S., Cliff, S., Bauguitte, S. J.-B., Young, S., Schwietzke, S., & Allen, G., Flaring efficiencies and NOx emission ratios measured for offshore oil and gas facilities in the North Sea, Atmospheric Chemistry and Physics, vol. 23, pp. 1491–1509, 2023. doi:10.5194/acp-23-1491-2023

[7] Gvakharia, A., Kort, E. A., Brandt, A., Peischl, J., Ryerson, T. B., Schwarz, J. P., Smith, M. L., & Sweeney, C., Methane, black carbon, and ethane emissions from natural gas flares in the Bakken Shale, North Dakota, Environmental Science & Technology, vol. 51, pp. 5317–5325, 2017. doi:10.1021/acs.est.6b05183

[8] Plant, G., Kort, E. A., Brandt, A. R., Chen, Y., Fordice, G., Gorchov Negron, A. M., Schwietzke, S., Smith, M., & Zavala-Araiza, D., Inefficient and unlit natural gas flares both emit large quantities of methane, Science, vol. 377, pp. 1566–1571, 2022. doi:10.1126/science.abq0385

[9] Cushing, L. J., Vavra-Musser, K., Chau, K., Franklin, M., & Johnston, J. E., Flaring from unconventional oil and gas development and birth outcomes in the Eagle Ford

Shale in South Texas, Environmental Health Perspectives, vol. 128, no. 7, pp. 077003-1–077003-10, 2020. doi:10.1289/EHP6394

[10] Fawole, O. G., Cai, X., Abiye, O. E., & MacKenzie, A. R., Dispersion of gas flaring emissions in the Niger delta: Impact of prevailing meteorological conditions and flare characteristics, Environmental Pollution, vol. 246, pp. 284–293, 2019. doi:10.1016/j.envpol.2018.12.021

[11] Caseiro, A., Gehrke, B., Rücker, G., Leimbach, D., & Kaiser, J. W., Gas flaring activity and black carbon emissions in 2017 derived from the Sentinel-3A Sea and Land Surface Temperature Radiometer, Earth System Science Data, vol. 12, pp. 2137–2155, 2020. doi:10.5194/essd-12-2137-2020

[12] Rutherford, J. S., Sherwin, E. D., Ravikumar, A. P., Heath, G. A., Englander, J., Cooley, D., Lyon, D., Omara, M., Langfitt, Q., & Brandt, A. R., Closing the methane gap in US oil and natural gas production emissions inventories, Nature Communications, vol. 12, p. 4715, 2021. doi:10.1038/s41467-021-25017-4

[13] Etminan, M., Myhre, G., Highwood, E. J., & Shine, K. P., Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing, Geophysical Research Letters, vol. 43, pp. 12614–12623, 2016. doi:10.1002/2016GL071930

[14] Höglund-Isaksson, L., Gómez-Sanabria, A., Klimont, Z., Rafaj, P., & Schöpp, W., Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe – results from the GAINS model, Environmental Research Communications, vol. 2, 025004, 2020. doi:10.1088/2515-7620/ab7457

[15] Roscioli, J. R., Herndon, S. C., Yacovitch, T. I., Knighton, W. B., Zavala-Araiza, D., Johnson, M. R., & Tyner, D. R., Characterization of methane emissions from five cold heavy oil production with sands (CHOPS) facilities, Journal of the Air & Waste Management Association, vol. 68, no. 7, pp. 671–684, 2018. doi:10.1080/10962247.2018.1436096

[16] Lauvaux, T., Giron, C., Mazzolini, M., d'Aspremont, A., Duren, R., Cusworth, D., Shindell, D., & Ciais, P., Global assessment of oil and gas methane ultra-emitters, Science, vol. 375, pp. 557–561, 2022. doi:10.1126/science.abj4351

[17] Olczak, M., Piebalgs, A., & Balcombe, P., A global review of methane policies reveals that only 13% of emissions are covered with unclear effectiveness, One Earth, vol. 6, pp. 519–532, 2023. doi:10.1016/j.oneear.2023.04.009

[18] European Parliament and Council, Regulation (EU) 2024/1787 of the European Parliament and of the Council on methane emissions reduction in the energy sector, Official Journal of the European Union, L, 2024. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32024R1787

[19] United Nations Environment Programme, Oil and Gas Methane Partnership 2.0: A new standard in methane emissions reporting, UNEP, 2020. https://www.ogmpartnership.org

[20] European Commission, Global Methane Pledge, European Commission & U.S. Department of State, 2021. https://www.globalmethanepledge.org

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CORPORATE SOCIAL RESPONSIBILITY AND SWOT ANALYSIS: THE CASE OF NIS COMPANY

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Abstract: The aim of this paper is to present the connection between Corporate Social Responsibility (CSR) and SWOT analysis through a case study of NIS, one of the largest energy companies in Southeast Europe. The theoretical framework covers the development of the CSR concept, with special emphasis on its economic, legal, ethical, and social aspects, as well as the specifics of its application in the energy sector. SWOT analysis was applied as a method for identifying strengths, weaknesses, opportunities, and threats in the company's operations, with results quantified through weighting and evaluation of key parameters. The findings show that NIS possesses significant internal potentials, such as tradition and a developed production system, but also weaknesses related to outdated infrastructure and geopolitical risks. The most important opportunities have been identified in the development of renewable energy sources and digitalization, while the greatest threats are volatility in energy prices and competition from the renewable energy sector. The discussion highlights that the implementation of CSR strategies, particularly in the fields of ecology and social development, has a direct impact on financial performance and the long-term sustainability of operations. The results confirm that the combination of CSR and SWOT analysis provides a useful framework for strategic planning in the context of the energy transition.
Key words: corporate social responsibility, SWOT analysis, NIS, sustainable development, energy sector

INTRODUCTION

In today's business environment, energy companies face the challenges of sustainable development, increasing societal demands, and regulatory pressures. In this context, Corporate Social Responsibility (CSR) has become a key framework that enables the balancing of economic, environmental, and social objectives. On the other hand, SWOT analysis is one of the most widely used tools in strategic management, as it allows for a systematic assessment of internal potentials and external factors that shape a company's competitive position.
The aim of this paper is to present, through a theoretical framework and a case study of NIS, the interconnection between CSR and SWOT analysis, as well as their significance for strategic decision-making in the energy industry. Special emphasis is placed on the identification of strengths, weaknesses, opportunities, and threats that shape NIS's operations, and on the analysis of how CSR contributes to risk reduction and the strengthening of competitive advantage.

MATERIAL AND METHODS

Corporate Social Responsibility (CSR)

Corporate Social Responsibility has evolved since the 1950s, when the idea was first formulated that companies, in addition to their economic role, also bear broader social obligations. During the 1960s and 1970s, the concept underwent intensive development through various definitions and approaches, eventually becoming a central framework for understanding the relationship between business and society [1].
CSR encompasses the overall framework through which concern for stakeholders is integrated into company strategies and day-to-day activities. In modern business practice, CSR is viewed

as a set of principles and practices that promote sustainable development, compliance with ethical standards, environmental protection, and active contribution to the community. Its implementation contributes to creating better living conditions for both present and future generations [2].

Today, CSR is increasingly seen as a strategic instrument for achieving competitive advantage and long-term sustainability. Research shows that strong corporate governance—such as board independence and diversity—enhances CSR performance and leads to more transparent reporting. High CSR performance is also linked to improved financial results, particularly in the environmental dimension, confirming that responsible business conduct simultaneously strengthens corporate reputation and market value [3].

CSR is also closely related to the achievement of the Sustainable Development Goals (SDGs), as it reduces risks, improves access to capital, and strengthens relationships with stakeholders. In this context, public policies and international standards play a crucial role, especially in the European Union, where mandatory reporting instruments and standardized frameworks such as GRI and ISO norms have been developed to increase transparency and accountability [4].

In the energy sector, CSR carries particular importance due to the high environmental and social risks associated with operations. Its three key pillars are social, environmental, and economic: investing in employees and communities, reducing emissions and transitioning to renewable energy sources, and ensuring reliable and efficient energy supply through continuous investments in new technologies. This approach reduces negative impacts and fosters long-term competitive advantage [5].

CSR also applies to internal stakeholders, with special emphasis on employees. Initiatives such as volunteering programs, donations, environmental projects, health and safety measures, and professional development contribute to stronger employee identification with the company, greater job satisfaction, and loyalty, while reducing turnover and risks. In this way, CSR benefits not only society and consumers but also the organization itself, by building a more stable and productive workforce [6].

SWOT Analysis

SWOT analysis is one of the most widely used tools in strategic management, as it allows for a systematic evaluation of internal and external factors shaping an organization's competitive position. The essence of this method lies in identifying strengths and weaknesses within the company, as well as opportunities and threats from the external environment, thereby providing a reliable basis for decision-making and adapting strategies to future challenges. Internal analysis covers resources, capabilities, and key competencies, including financial, infrastructural, and innovation capacities, managerial skills, and brand value. External analysis refers to opportunities and threats from the wider environment, based on political, economic, social, and technological factors, as well as industry competition. In this way, SWOT links internal organizational potentials with external conditions and enables the formulation of sustainable strategies [7].

In modern business conditions, advanced models have been developed to enhance the traditional SWOT framework. Integrated approaches combine data and metrics from different industries and digital systems, helping to avoid common shortcomings of SWOT such as superficial interpretation and the absence of action plans. Such approaches confirm that SWOT remains an important tool of strategic planning, but its application must be supported by standardized frameworks and digital tools to ensure relevant and applicable results [8].

Extensive application across sectors has demonstrated that SWOT analysis remains a flexible and effective tool for strategic decision-making. When properly applied, it goes beyond the mere listing of factors and is linked with the TOWS matrix, which enables the development of effective strategies by combining internal and external dimensions. Furthermore, integrating SWOT with tools such as PESTEL analysis or multi-criteria methods (AHP, ANP) provides more precise and actionable outcomes, reaffirming SWOT's central role in contemporary management [9].

CASE STUDY: NIS COMPANY

About NIS Company

The Petroleum Industry of Serbia (NIS) is one of the largest energy companies in Southeast Europe and represents a vertically integrated system that covers the entire business chain – from exploration and production to refining, distribution, and sales of oil derivatives. In addition to its core activities, the company is also active in the development of renewable energy sources and petrochemicals. NIS operates with its headquarters and main facilities in the Republic of Serbia, including the Pančevo Oil Refinery, a network of gas stations, and storage capacities. The company's mission is based on efficient operations, investment in technologies and human resources, as well as the development of the community in which it operates. The ownership structure includes "Gazprom Neft" with 44.85% of shares, the Republic of Serbia with 29.87%, "Gazprom" with 11.30%, while the remainder belongs to citizens, employees, and minority shareholders [10].

CSR in NIS Company

In line with its sustainable development strategy, NIS develops a wide range of activities within corporate social responsibility.
The **ecological dimension** includes the remediation of historical pollution and returning land to agricultural use, reducing emissions and installing solar panels at gas stations, as well as implementing HSE standards and preventive measures in environmental protection. In addition, the company participates in local environmental initiatives such as afforestation and recycling, which confirms its strategic approach to reducing the impact on climate change.
The **social responsibility** of NIS is reflected in investments in local communities through the "Together for the Community" program, support for educational, cultural, and healthcare institutions, as well as employee engagement through the Volunteer Club. The company develops student internship programs and continuously invests in the education and training of employees. Special emphasis is placed on occupational safety and reducing professional illnesses, which is part of a broader policy of ensuring safe and healthy working conditions. In this way, NIS strengthens its position as a desirable employer and a reliable partner to the local community [11].
The **economic responsibility** of the company is reflected in investments exceeding four billion euros since 2009, including modernization of infrastructure, improvement of technological processes, and the development of new capacities. NIS is actively involved in the digitalization and automation of business processes, which contributes to increased competitiveness and efficiency. In addition, the company invests in energy efficiency of refineries and distribution facilities and ensures transparency through regular reporting in accordance with international standards (GRI).
The **ethical dimension** of NIS corporate responsibility includes compliance with laws and the fight against corruption, ensuring equal opportunities for all employees, alignment with international business standards, and transparent reporting of results. The company promotes responsible supply chain relations, with special emphasis on respect for human rights and ethical business practices with suppliers. In this way, NIS confirms its commitment to sustainability, integrity, and responsible business operations at all levels [12].

SWOT Analysis of NIS Company

SWOT analysis provides a comprehensive overview of the company's internal potentials as well as external factors that affect its market position. Based on the presented data, an assessment of NIS strengths, weaknesses, opportunities, and threats was conducted, with weighted values showing the relative importance of each factor.
Table 1 presents the strengths of NIS company.

Table 1. *Strengths of NIS Company*

STRENGTHS	
Parameter: **Tradition**	Weight: 0,6
Sub-parameters:	Score:
Loyalty:	8
Brend:	10
Average score:	(8+10)/2=9
Factor/parameter score:	0,6*9=**5,4**
Parameter: **Production system**	Weight: 0,8
Sub-parameters:	Score:
Exploration (oil and gas):	8
Refining and distribution:	9
Average score:	(8+9)/2=8,5
Factor/parameter score:	0,8*8,5=**6,8**

The company's strengths stem from its long-standing tradition and a well-developed production system. Decades of experience, a strong brand, and a loyal customer base ensure market stability, while control over the entire production chain—from exploration to sales—enhances efficiency and competitiveness. These strengths enable NIS to maintain its leading position in the region and to adapt more easily to market changes.
Table 2 presents the weaknesses of NIS company.

Table 2. *Weknesses of NIS Company*

WEKNESSES	
Parameter: **Obsolete infrastrucure**	Weight: 0,7
Sub-parameters:	Score:
Equipment age:	8
Maintenance costs:	7
Average score:	(8+7)/2=7,5
Factor/parameter score:	0,7*7,5=**5,25**
Parameter: **Geopolitical vulnerability**	Weight: 0,8
Sub-parameters:	Score:
Ownership ties with Russia:	9
Risk of sanctions:	9
Average score:	(9+9)/2=9
Factor/parameter score:	0,8*9=**7,2**

The weaknesses are primarily related to outdated infrastructure, which increases costs and slows modernization, as well as geopolitical vulnerability due to ownership structure, which brings significant risks in crisis international circumstances, such as sanctions. These weaknesses require careful and strategic management.
Table 3 presents the opportunities of NIS company.

Table 3. *Opportunities of NIS Company*

OPPORTUNITIES	
Parameter: **Development of renewable energy sources**	Weight: 0,9
Sub-parameters:	Score:
Solar power plants:	8
Wind farms:	9
Average score:	(8+9)/2=8,5
Factor/parameter score:	0,9*8,5=**7,65**
Parameter: **Digitalization and innovations**	Weight: 0,7
Sub-parameters:	Score:
Automation:	9
Digital services for customers:	7
Average score:	(9+7)/2=8
Factor/parameter score:	0,7*8=**5,6**

The most significant opportunities for the company lie in the development of renewable energy sources and digitalization. These are rapidly growing sectors globally, and NIS has already invested in solar panels and digital customer services, which demonstrates alignment with global trends. If properly utilized, these opportunities can bring long-term competitive advantages and ensure sustainable growth.
Table 4 presents the threats of NIS company.

Table 4. *Threats of NIS Company*

THREATS	
Parameter: **Changes in oil and gas prices**	Weight: 0,9
Sub-parameters:	Score:
Market availability:	7
Impact of global conflicts:	8
Average score:	(7+8)/2=7,5
Factor/parameter score:	0,9*7,5=**6,65**
Parameter: **Competition**	Weight: 0,6
Sub-parameters:	Score:
Small distributors:	5
Transition to renewable energy sources:	8
Average score:	(5+8)/2=6,5
Factor/parameter score:	0,6*6,5=**3,9**

The most significant threats arise from the external environment, namely the volatility of energy prices and increasing competition in the renewable energy sector. These changes can strongly affect revenue and market share, especially if the company fails to adapt quickly. Strategic diversification and investments in innovation are therefore essential to mitigate risks.

Overall conclusion for SWOT

The comprehensive analysis shows that NIS possesses strong internal potentials but also faces challenges that require careful management. By maximizing its strengths and opportunities—tradition, brand, production system, investments in renewables, and digital technologies—while minimizing weaknesses and threats, the company can position itself as a responsible, modern, and sustainable player in the energy transition and further strengthen its role as a regional leader.

RESULTS AND DISCUSSION

The analysis shows that corporate social responsibility (CSR) has a direct impact on the economic performance and competitive position of companies. As emphasized earlier, CSR performance, particularly in the environmental dimension, positively influences financial results, reputation, and market value. In the case of NIS, this is confirmed through investments in renewable energy, environmental protection projects, and human resource development, which not only contribute to society but also strengthen the company's market position and reduce external risks.

Public policies and international standards, such as GRI and ISO 14001, encourage companies to enhance transparency and accountability through institutionalized CSR practices. In the context of NIS, alignment with these standards represents an important opportunity to reduce regulatory risks and strengthen stakeholder trust, which is fully consistent with the opportunities identified in the SWOT analysis.

The specific features of the energy sector, which faces significant environmental and social challenges, indicate that CSR integration brings competitive advantages. For NIS, this means that investments in environmental projects and social initiatives are not merely costs but also instruments of risk reduction and long-term sustainability.

From the perspective of technological innovation, Hajizadeh (2019) highlights that the application of machine learning in the oil and gas industry creates significant opportunities to improve efficiency and safety. Digitalization and automation of processes, supported by advanced ML technologies, can be an important opportunity for companies such as NIS to strengthen their competitive position, but at the same time pose threats if skilled personnel and systemic support are not secured.

Theoretical literature also confirms that SWOT analysis, when applied analytically, enables managers to develop effective strategies by linking internal strengths with external opportunities and threats. By combining insights from the theoretical framework and practical analysis, it becomes clear that CSR strategies and SWOT analysis are not isolated tools but complementary approaches. While CSR contributes to sustainability and competitiveness, SWOT analysis facilitates the identification of internal and external factors that can accelerate or hinder the implementation of these strategies. In the case of NIS, this interconnection confirms that socially responsible business practices and strategic planning together form the foundation for long-term resilience and successful positioning in the energy transition.

CONCLUSION

Drawing on its experience and tradition, yet facing infrastructural and geopolitical challenges, NIS represents a typical example of a company that must balance internal potentials with external risks. The SWOT analysis revealed that the company's key strengths are a strong brand, loyal customers, and a developed production system, while its weaknesses include outdated infrastructure and risks associated with ownership structure. At the same time, opportunities for growth were identified in the transition to renewable energy sources and digitalization, whereas threats stem from energy price volatility and increasing competition.

The discussion confirmed that CSR strategies significantly contribute to long-term sustainability, strengthening stakeholder trust, and mitigating identified threats. Investments in ecology, the community, and human resources are not merely costs but mechanisms for

enhancing market position and reputation. By combining the results of the SWOT analysis with the application of CSR principles, NIS can position itself as a responsible and modern company capable of leading the energy transition in the region.

REFERENCES

[1] Carroll, A.B. (1999). Corporate Social Responsibility: Evolution of Definitional Construct. Business & Society, 38(3), 268-295.
[2] Carroll, A. B. (2015). Corporate Social Responsibility: The centerpiece of competing and complementary frameworks. Organizational Dynamics, 44(2), 87–96. https://doi.org/10.1016/j.orgdyn.2015.02.002
[3] Velte, P. (2022). Meta-analyses on Corporate Social Responsibility (CSR): a literature review. Management Review Quarterly, 72, 627–675. https://doi.org/10.1007/s11301-021-00211-2
[4] Lu, J., Ren, L., Lin, W., He, Y., & Streimikis, J. (2019). Policies to Promote Corporate Social Responsibility (CSR) and Assessment of CSR Impacts. E+M Economics and Management, XXII(1), 82–98. https://doi.org/10.15240/tul/001/2019-1-006
[5] Stjepcevic, J., & Siksnelyte, I. (2017). Corporate Social Responsibility in Energy Sector. Transformations in Business & Economics, 16(1), 21–33.
[6] Al Halbusi, H., & Tehseen, S. (2017). Corporate Social Responsibility (CSR): A Literature Review. Malaysian Journal of Business and Economics, 4(2), 30–48.
[7] Sammut-Bonnici, T., & Galea, D. (2015). SWOT Analysis. In C. L. Cooper (Ed.), Wiley Encyclopedia of Management (3rd ed.). John Wiley & Sons. https://doi.org/10.1002/9781118785317.weom120103
[8] Namugenyi, C., Nimmagadda, S. L., & Reiners, T. (2019). Design of a SWOT Analysis Model and its Evaluation in Diverse Digital Business Ecosystem Contexts. Procedia Computer Science, 159, 1145–1154. https://doi.org/10.1016/j.procs.2019.09.283
[9] Benzaghta, M. A., Elwalda, A., Mousa, M. M., Erkan, I., & Rahman, M. (2021). SWOT Analysis Applications: An Integrative Literature Review. Journal of Global Business Insights, 6(1), 55–73. https://doi.org/10.5038/2640-6489.6.1.1148
[10] https://www.nis.rs/
[11] Izveštaj o održivoj razvoju NIS Grupe za 2024. godinu
[12] Godišnji izveštaj NIS Grupe za 2024. godinu
[13] Hajizadeh, Y. (2019). Machine learning in oil and gas; a SWOT analysis approach. Journal of Petroleum Science and Engineering, 176, 661–663. https://doi.org/10.1016/j.petrol.2019.01.113

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MODELING ISOBUTANE UNCONTROLLED RELEASE FROM A STORAGE TANK

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Abstract: This work represents a modeling isobutane uncontrolled release from a classic horizontal cylindrical storage tank of 141 m^3 and its negative aspect on the environment. Accident modeling is a key part of risk assessment in the chemical industry. Risk assessment in the chemical industry is a prerequisite for reducing or avoiding possible accident situations. By recognizing and identifying the critical points of a system and its proper and safe management, the risk is reduced to the lowest possible probability and extent of consequences.
Key words: isobutane, storage leaking, accidents, chemical industry

INTRODUCTION

Isobutane (C_4H_{10}), an isomer of n-butane, is often used as a raw material in petrochemical industry, a refrigerant, a component in aerosols, and as a fuel. However, precisely because of its low vaporization point and wide explosive range in air, it poses a significant safety challenge. Uncontrolled release of isobutane, especially from large storage tanks, can lead to the formation of flammable clouds and serious incidents, including fires, explosions and chemical contamination of the environment. Therefore, it is necessary to develop methodologies for the prediction and analysis of such scenarios, in order to reduce the risk and protect human lives and resources.
For this purpose, software tools have been developed that enable the simulation of chemical accidents and the assessment of consequences in controlled conditions. Among them, ALOHA (Areal Locations of Hazardous Atmospheres) stands out – an advanced software that enables the visualization and quantification of potentially hazardous zones resulting from chemical leaks. ALOHA, developed by the United States Environmental protection agency (EPA), uses input data on the physicochemical properties of the substance, atmospheric conditions and location characteristics to generate realistic projections of the spread of pollutants and the extent of the hazard.

MATERIAL AND METHODS

Characteristics of isobutane

Isobutane (C_4H_{10}) belongs to the group of saturated hydrocarbons, alkanes. Under standard conditions (25°C, 1 atm) it is a colorless gas with a characteristic odor, with a pronounced flammability and a low boiling point. Its molecular weight is 58.12 g/mol, while the boiling point is −11.7°C, which means that isobutane is in a gaseous state even at room temperature. The density of gaseous isobutane is about 2.7 kg/m^3, which is approximately twice the density of air. Due to this property, isobutane is classified as a so-called "heavy gas" and tends to remain on the ground in the event of a leak, especially in adverse atmospheric conditions.
Isobutane is extremely flammable. It will be easily ignited by heat, sparks or flames. Will form explosive mixtures with air. Vapors from liquefied gas are initially heavier than air and spread along ground [1,2].
The main physical and chemical characteristics of isobutane are listed in the table 1.

Table 1. *Physical and chemical characteristics of isobutane [3]*

The parameters	Units	Values
Molecular mass	g/mol	58,12
Boiling point	°C	-11,7
Melting point	°C	-159,6
Density (gas at 0°C, 1 atm)	kg/m³	2,67
Relative density (relative to air)	–	2,01
Lower Explosive Limit (LEL)	% vol.	1,8
Upper Explosive Limit (UEL)	% vol.	8,4
Flash point	°C	-83
Self-igniting temperature	°C	460
Heat of combustion	kJ/mol	2877
Specific heat	kJ/kgK	1,67

Due to its physical and chemical properties (low evaporation point, high flammability and tendency to remain on the ground), isobutane poses a serious hazard in case of release or accidents. Accidents involving isobutane can have far-reaching consequences for people, property and the environment, especially in industrial areas with close residential houses.

Modeling isobutene leakage from a storage tank

Isobutane uncontrolled release from a storage tank in industrial plants can have serious consequences, especially when this gas is stored in large quantities under pressure. Pipeline failures, tank cracks, leaking gaskets, flanges, unreliable valves, or mechanical damage due to the corrosion typically causes this accident. In addition to physical damage to the system, releases can also occur during filling, emptying and equipment maintenance operations, especially if the procedures are not carried out in accordance with prescribed standards. Isobutane, as a gas with a higher density than air, tends to spread and keep close to the ground, collecting in depressions, ducts and closed spaces. Thus increasing the risk of forming an explosive mixture in contact with a flammable source.
ALOHA (Areal Locations of Hazardous Atmospheres) is a specialized software tool developed for modeling the atmospheric dispersion of hazardous chemicals, primarily in emergency situations. The software is developed by the US Environmental Protection Agency (EPA) and the National Oceanic and Atmospheric Administration (NOAA). The goal of its development was to enable a quick and reliable assessment of the potential spread of dangerous clouds in the atmosphere after a chemical leak, whether it is an accidental industrial accident or a terrorist incident. ALOHA allows you to enter details about a real or potential chemical release, and then it will generate threat zone estimates for various types of hazards. Threat zones can also be shown in Google Earth or Google Maps using ALOHA's KML export feature.
ALHOA models have three hazard categories: toxic gas dispersion, fires, and explosions. ALOHA employs several different models, including an air dispersion model that it uses to estimate the movement and dispersion of chemical gas clouds. From this model, ALOHA is able to estimate the toxic gas dispersion, the overpressure values from a vapor cloud explosion, or the flammable areas of a vapor cloud. ALOHA uses additional models to estimate the hazards associated with other fires and explosions.
When a gas that is heavier than air is released, it initially behaves very differently from a neutrally buoyant gas. The heavy gas will first "slump," or sink, because it is heavier than the surrounding air. As the gas cloud moves downwind, gravity makes it spread; this can cause some of the vapor to travel upwind of its release point. Farther downwind, as the cloud becomes more diluted and its density approaches that of air, it begins behaving like a neutrally buoyant gas. This takes place when the concentration of heavy gas in the surrounding air drops below about 1 percent (10,000 parts per million). For many small releases, this will occur in the first few meters. For large releases, this may happen further downwind [4].

All of the accidents that can be modeled in the ALOHA software are based on the physical and chemical characteristics of substances and weather conditions that are present at the time of accident. The weather conditions that are entered as input parameters for modeling of accidents are the most common temperatures, wind speeds and directions in the last decade. Sometimes, in real situations opposite weather conditions occur than those predicted in risk assessments but that are the limitations of the software tools.

RESULTS AND DISCUSSION

In this paper will be presented the modeling of isobutene uncontrolled release from a concrete tank with a volume of 141m^3 using the ALOHA software. In the following table 2 are given the input data used in the software.

Table 2. *Input parameters for isobutane uncontrolled release simulation in ALOHA software*

Category	Parameter	Value/Description
1. Chemical substance	State of substance	Compressed gas under pressure
	Chemical temperature	22°C
	Tank pressure	2.5 bar
2. Tank and hole	Tank type	Horizontal cylindrical tank
	Tank dimensions	Diameter: 3 m, Length: 20 m
	Opening type	Round hole
	Opening dimensions	3 cm
	Opening orientation	Lateral, west side of the tank
	Opening angle to the direction of the wind	0° (directly in the direction of the wind)
	Duration of release	Continuous / until empty
3. Meteorological conditions	Wind speed	5 m/s
	Wind direction	North
	Air temperature	25°C
	Relative humidity	50%
	Cloudiness	7
	Time of day	Day / Sunny

The results obtained from the ALOHA software show the formation of three danger zones corresponding to different concentrations of isobutane in the air. The most critical is the red zone (LEL × 60%), which represents an immediate danger of the formation of pockets of flame and possible instantaneous ignition. In this case, that zone extended 34 meters from the point of leakage. Next is the orange zone, which indicates the area where the concentration reaches the lower explosive limit (LEL) up to 26m, and then the yellow zone, which extends up to 104 meters from the source, with a concentration of 10% LEL, and indicates the area of possible inhalation, odor and presence of flammable vapors. Threat zones are presented on the following figure 1.

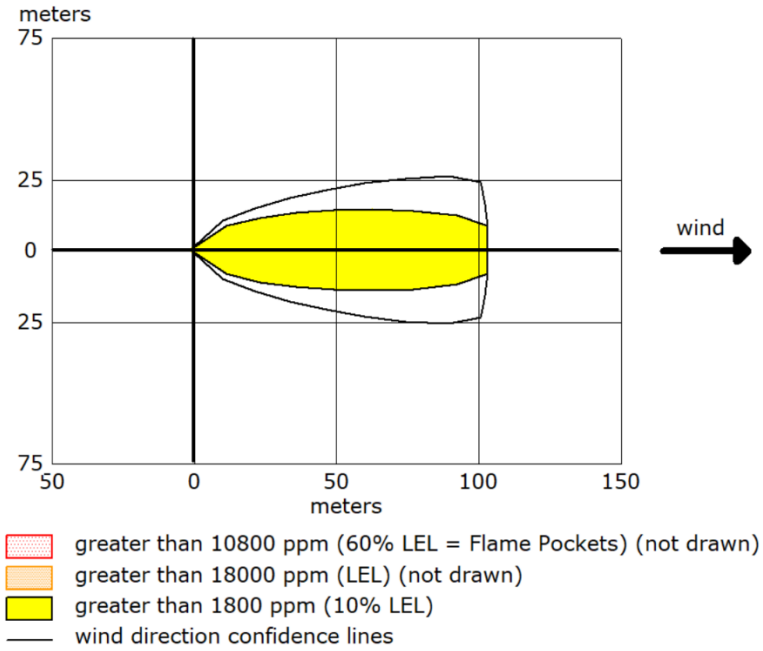


Fig. 1. *Threat zones of simulated accident*

Figure 2 shows a graph representing the simulation of isobutane concentration at a distance of 150 meters downwind of the release site. This analysis was performed using the ALOHA software package, with the aim of showing the influence of time on the accumulation of flammable gases both in open (outdoor) space and inside closed buildings. The model enables a quantitative assessment of the dynamics of gas expansion and its penetration into objects, which is of particular importance for making operational and safety decisions in real time during chemical incidents.

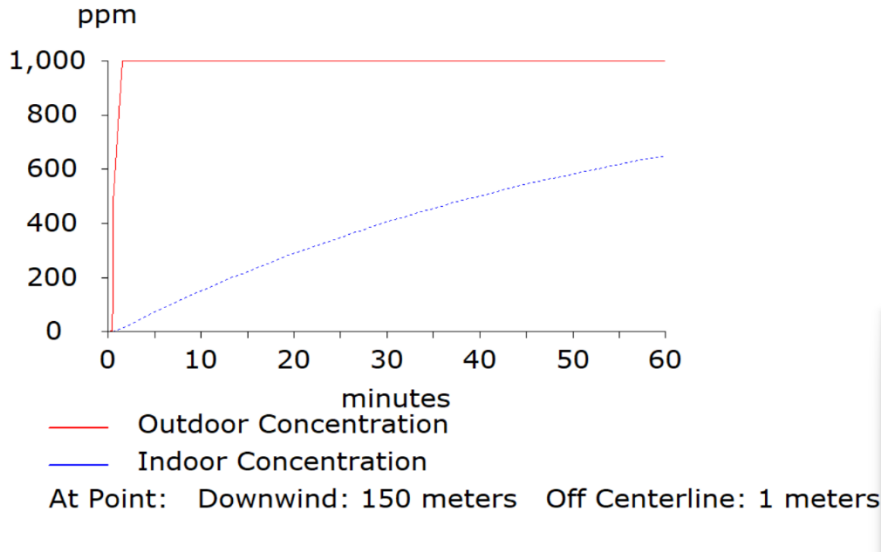


Fig. 2. *Graphic representation of isobutane concentration at a distance of 150m from the point of release*

The x-axis at the figure 2 shows time in minutes, while the y-axis is reserved for isobutane concentration in ppm (parts per million). The two curves give a comparison between:

- Red lines (Outdoor Concentration) - concentration of isobutane in the external atmosphere. It can be observed that the concentration suddenly reaches a maximum (~1000 ppm) already in the first minutes after the start of the leak, which indicates a

very fast dispersion of the gas in the direction of the wind. This value remains stable, because it is a constant release of the substance during the simulated time period.

- Blue lines (Indoor Concentration) – concentration of isobutane inside a closed space, at the same distance of 150 meters, but with a minimal shift from the wind axis (1 meter on the side). This line shows the gradual increase in concentration in a closed facility, due to slower gas penetration through the structure of the facility (windows, doors, ventilation). After 60 minutes, the indoor concentration reaches about 600 ppm, which is significantly lower than the outdoor value, but still poses a serious risk.

The results from a modeling indicate that even in a relatively short period of time, it is possible to form a significant amount of flammable mixture in the atmosphere, especially in zones with slow ventilation. It is important to emphasize that in real situations the duration and rate of release may vary, and the actual values may be lower, but simulations of this type are used as a tool for designing protection systems, including automatic valve closing, sensor activation, evacuation and plant zoning.

CONCLUSION

In this paper ALOHA software was used to model uncontrolled release from a concrete storage tank, with input of realistic parameters such as pressure, opening size and weather conditions. The obtained results are presented through figures that define the danger zones, with a special emphasis on the range of the flammable mixture and the potentially endangered population or property.

Effective management of the risk of isobutane uncontrolled release requires an interdisciplinary approach - combining engineering knowledge, information technology, legal framework and industrial practice. Software simulations, such as ALOHA, are necessary for the preventive identification of potentially dangerous zones, while the application of laws and standards are the basis for a legally and technically correct response in the case of an accident.

REFERENCES

[1] National Center for Biotechnology Information. PubChem Compound Summary for Isobutane. Retrieved September 2, 2025 from https://pubchem.ncbi.nlm.nih.gov/compound/Isobutane, 2025.
[2] Pohanish R., Sittig's Handbook of Toxic and Hazardous Chemicals and Carcinogens, Seventh Edition, ISBN 978-0-323-38968-6, 2017.
[3] NIS a.d. Novi Sad.. Material Safety Data Sheet: Izobutan (MSDS), 2023.
[4] US Environmental Protection Agency, Office of Emergency Management, National Oceanic and atmospheric administration, Office of Response and Restoration Emergency Response Division: Aloha User´s manual, Washington DC, 2007.



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CIRCULAR SUPPLY CHAIN PRACTICES AND THEIR CONTRIBUTION TO GREEN ECONOMY GOALS IN SERBIAN MANUFACTURING

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Abstract: The transition toward a green economy requires manufacturing firms to adopt more sustainable and circular supply chain practices. This study explores the extent to which Serbian manufacturers implement three key circular strategies—recycling and material recovery, product life extension, and reverse logistics—and how these practices contribute to alignment with environmental objectives. Based on survey data collected from 32 companies, the analysis applies regression modeling to evaluate the relationship between these practices and perceived alignment with green economy goals. Results show that recycling and product life extension significantly influence environmental alignment, while reverse logistics demonstrates a weaker, non-significant effect. The findings underscore the strategic importance of circular initiatives and highlight areas where greater institutional and infrastructural support is needed to accelerate sustainable industrial development.
Key words: circular economy, supply chain management, green manufacturing, sustainable logistics

INTRODUCTION

Circular supply chain practices have gained considerable attention in recent years as a response to the growing pressure on industries to reduce environmental impact while maintaining operational efficiency. Traditional supply chains are typically linear in nature, involving the extraction of raw materials, production, consumption, and ultimately, disposal. In contrast, circular supply chains emphasize the recirculation of materials and the minimization of waste through a closed-loop model[1]. The fundamental goal is to retain the value of products, components, and materials for as long as possible through activities such as recycling, remanufacturing, reuse, and reverse logistics. These activities are not merely add-ons but are being integrated strategically into the supply chain to achieve long-term sustainability and cost-effectiveness.

In practical terms, recycling and material recovery refer to the systematic processing of waste materials into reusable resources. In manufacturing contexts, this could involve the collection of scrap metal, plastic, or other production residues and their reintegration into the production process either internally or through third-party recyclers[2]. Product life extension, on the other hand, focuses on strategies such as refurbishing, reconditioning, and designing products for disassembly and reuse. This not only reduces the demand for virgin materials but also aligns production with consumer trends favoring sustainable products. Reverse logistics, which deals with the movement of goods from the end user back to the manufacturer or a secondary facility, supports these goals by enabling the return and proper handling of used or faulty products[3]. The adoption of these practices depends on several factors, including organizational culture, regulatory environment, customer expectations, and technological capability. In developed markets, circular supply chains are often supported by robust infrastructure and policy incentives[4]. In developing or transitioning economies, such as Serbia, the situation is more complex. Companies must often invest in new technologies, redesign existing supply chain processes, and train personnel to support circular operations. Despite these challenges, firms that successfully integrate circular logistics can experience several advantages, including improved resource utilization, enhanced brand reputation, and reduced operational risks.

The transition to a green economy requires industries to rethink how economic activities are structured and evaluated. A green economy promotes environmentally sustainable and socially inclusive growth by decoupling economic development from environmental

degradation[5]. In this context, supply chains are viewed as critical systems where environmental improvements can be realized at scale. Logistics operations, in particular, have a direct impact on energy consumption, emissions, and waste production, making them key targets for intervention. The integration of circular supply chain practices thus becomes a practical mechanism for firms to contribute to green economy objectives in measurable ways.

BACKGROUND RESEARCH

Serbian manufacturing firms operate within a dynamic and often challenging industrial landscape shaped by a combination of legacy infrastructure, evolving environmental regulations, and increasing pressure from global supply chain partners[6]. As sustainability becomes a more integral part of international trade and production standards, the capacity of Serbian manufacturers to adapt is critical. While there is growing awareness of environmental concerns, the pace of circular economy adoption remains uneven across sectors and regions. Larger firms with international exposure are more likely to integrate recycling, reuse, and reverse logistics into their operations, while small and medium-sized enterprises (SMEs) may struggle due to limited resources, expertise, or strategic direction[7]. Nevertheless, the broader trend is moving toward sustainability, driven both by regulatory alignment with the European Union and by economic incentives such as energy cost savings and access to green funding. Some firms have established basic material recovery systems, while others have gone further to integrate remanufacturing and reverse logistics capabilities into their operations. Still, many companies perceive sustainability initiatives as a cost rather than an investment, leading to a fragmented adoption landscape. Industry-specific factors also play a role. For example, sectors like food processing or chemicals may face stricter waste management obligations, whereas textile or machinery manufacturers may have more flexibility in how they apply circular principles[8]. Organizational culture, managerial awareness, and access to technical knowledge further influence the extent to which firms engage in circular logistics. These variables form the backdrop against which environmental performance is measured and evaluated in this study.

Despite the obstacles, there are clear signs of transition. Environmental awareness is steadily growing among both producers and consumers, and government programs increasingly support cleaner production methods[9]. Non-governmental organizations and academic institutions also contribute to capacity building by promoting best practices and facilitating knowledge exchange. Moreover, green procurement policies and international certifications such as ISO 14001 encourage firms to align their supply chain operations with sustainability targets[10]. However, translating awareness and compliance into measurable environmental gains requires robust tools for analysis and decision-making. It is in this space that data-driven methodologies can provide significant value, allowing firms to quantify the benefits of circular logistics and make informed strategic choices.

The use of empirical data to assess sustainability practices in supply chains is essential for bridging the gap between theory and implementation. Conceptual models and policy recommendations offer useful guidance, but only through systematic analysis can the true impact of circular practices be verified. This study responds to that need by designing a framework for measuring key circular logistics activities—recycling and recovery, product life extension, and reverse logistics—and analyzing their influence on green economy alignment. These elements form the foundation for the descriptive and regression analysis that follows, offering insights into the environmental value of circular supply chain strategies.

METHODOLOGY

The research aims to empirically examine the influence of circular supply chain practices on the environmental orientation of manufacturing firms, conceptualized as alignment with green economy goals. A structured survey was conducted with 32 respondents drawn from middle and upper management levels in Serbian manufacturing companies across various sectors, including metal processing, plastics, food production, and electronics. Respondents provided

assessments on a 7-point Likert scale (1 = strongly disagree, 7 = strongly agree) to evaluate the extent of implementation of three independent constructs and one dependent construct.
The independent variables include:

- Recycling and material recovery (REC): This construct captures the extent to which companies systematically collect, sort, and reintegrate recyclable materials into production processes. It includes practices such as internal recycling of production waste, collaboration with third-party recyclers, and resource recovery initiatives.
- Product life extension and reuse (PLE): This variable reflects efforts to prolong the useful life of products and components through design, maintenance, and refurbishment strategies. It includes modular product design, repair services, and remanufacturing practices aimed at reducing the need for new materials and minimizing environmental impact.
- Reverse logistics and returns (RLR): This dimension refers to the systems and processes enabling the return, collection, and reprocessing of used or end-of-life products. It includes organized take-back schemes, repair networks, and logistics solutions for transporting returned goods to appropriate facilities for reuse or recycling.

The dependent variable is defined as:

- Green economy alignment (GEA): This construct represents the firm's perceived alignment with broader ecological goals such as energy efficiency, waste minimization, circular resource flow, and compliance with environmental standards.

The internal consistency of all constructs was tested using Cronbach's Alpha. Mean scores and standard deviations were calculated to present the general trends and distribution of responses. Multiple linear regression analysis was applied to explore the predictive power of the three circular supply chain practices on green economy alignment. Model diagnostics included the coefficient of determination (R^2), adjusted R^2, variance inflation factor (VIF), and Durbin-Watson statistic to test for multicollinearity and residual independence.
The research is guided by the following hypotheses:

- H1: Recycling and material recovery practices have a significant positive effect on green economy alignment in Serbian manufacturing.
- H2: Product life extension and reuse practices significantly contribute to alignment with green economy goals.
- H3: Reverse logistics and returns are positively associated with green economy alignment in manufacturing firms.

RESULTS

The results from Table 1 present the descriptive statistics for each of the key constructs. Mean values range from 5.21 to 5.88, indicating a relatively high perceived implementation of circular supply chain practices among surveyed firms. Recycling and material recovery received the highest average score (M = 5.88), suggesting this is the most widespread practice. Reverse logistics shows the lowest mean (M = 5.21), indicating more variability and possibly more barriers to implementation in this area.
The internal reliability of all constructs is strong, with Cronbach's Alpha values above the acceptable threshold of 0.70. This confirms that the items used to measure each variable demonstrate internal consistency. The high reliability values provide a solid foundation for conducting further inferential statistical analysis and interpreting results with confidence.

***Table 1**. Descriptive statistics and reliability analysis*

Variable	Mean	Std. Dev.	Cronbach's Alpha
REC	5.88	0.76	0.81
PLE	5.55	0.84	0.79
PLR	5.21	0.95	0.77
GEA	5.67	0.69	0.83

Table 2 presents the results of the multiple linear regression analysis examining the effects of the three independent variables on green economy alignment. Both recycling and product life extension variables have statistically significant effects at the 0.05 level, with standardized beta coefficients of 0.412 and 0.378, respectively. This suggests that firms placing greater emphasis on these two circular practices are more likely to align with green economy goals. Reverse logistics, while positively related, does not reach conventional significance, indicating that its influence may be more context-dependent or constrained by implementation challenges.
The overall model explains approximately 59.4% of the variance in green economy alignment ($R^2 = 0.594$), and the adjusted R^2 value of 0.552 confirms the robustness of the model. The F-statistic is significant ($p < 0.001$), demonstrating that the regression model provides a statistically reliable explanation of the relationship between circular supply chain practices and environmental orientation. These findings reinforce the relevance of circular logistics in achieving sustainable industrial goals.

***Table 2.** Multiple linear regression results*

Independent Variable	Beta	t	Sig. (p-value)
REC	0.412	2.47	0.020*
PLE	0.378	2.31	0.026*
PLR	0.291	1.88	0.069
$R^2 = 0.594$	Adjusted $R^2 = 0.552$	F = 14.87	Sig. = 0.000

H1: Recycling and material recovery practices have a significant positive effect on green economy alignment in Serbian manufacturing. Confirmed. The regression analysis shows a statistically significant positive effect ($\beta = 0.412$, $p = 0.020$), supporting the hypothesis.
H2: Product life extension and reuse practices significantly contribute to alignment with green economy goals. Confirmed. The standardized coefficient for this variable is statistically significant ($\beta = 0.378$, $p = 0.026$), validating the hypothesis.
H3: Reverse logistics and returns are positively associated with green economy alignment in manufacturing firms.Not confirmed. Although the coefficient is positive ($\beta = 0.291$), the effect is not statistically significant at the 0.05 level ($p = 0.069$), and thus the hypothesis is not supported.

Table 3 summarizes the diagnostic tests conducted to validate the regression model. The Durbin-Watson value of 2.09 indicates no signs of autocorrelation in the residuals, which supports the independence assumption in the regression analysis. Variance Inflation Factor (VIF) scores for all independent variables are below 2.0, confirming that there are no multicollinearity issues among predictors, and each variable contributes uniquely to the model.
In addition, the distribution of residuals was evaluated using normal probability plots and histogram analysis, which showed an approximately normal distribution. These diagnostics confirm the validity of the regression model and support the conclusion that the estimated relationships are both statistically and practically meaningful. The absence of diagnostic

violations improvesthe credibility of the findings and reinforces the model's suitability for explaining the role of circular practices in supporting green economy objectives.

Table 3. *Model diganostics*

Diagnostic Test	Result	Interpretation
Durbin-Watson	2.09	No autocorrelation
VIF (all variables)	<2.0	No multicollinearity
Residuals Normality	Satisfied	Distribution is approximately normal

DISCUSSION

The findings of this study highlight the pivotal role that specific circular supply chain practices play in enhancing green economy alignment among Serbian manufacturing firms. The high mean scores for all three independent variables indicate a generally favorable attitude toward circular practices, suggesting that sustainability is increasingly integrated into operational strategy. Notably, recycling and material recovery emerged as the most widely implemented strategy. This could be attributed to the relatively low entry barriers for adopting recycling procedures, as well as the presence of both regulatory support and financial incentives for materials recovery in Serbia. In contrast, reverse logistics demonstrated lower average implementation, potentially reflecting infrastructural or logistical constraints that hinder its widespread adoption.

Regression analysis confirmed that both recycling and product life extension practices have statistically significant and positive effects on green economy alignment. These findings suggest that companies that invest in internal recycling systems and design products for durability are more likely to perceive alignment with sustainability goals. The statistical insignificance of reverse logistics, while still positively correlated, suggests either inconsistent implementation or a lack of visibility in its environmental benefits. This is a critical insight for both practitioners and policymakers, as it points to a need for targeted interventions and infrastructure development to facilitate the return and reuse of products.

From a managerial standpoint, the results reinforce the importance of embedding circularity into strategic planning and day-to-day operations. Firms that view circular practices not merely as regulatory compliance but as levers for innovation and competitiveness are better positioned to meet evolving environmental standards and consumer expectations. Furthermore, the integration of these practices may enhance brand reputation and open access to sustainability-linked financing opportunities. In this context, the statistical significance of product life extension strategies is particularly notable, as it aligns with global trends in modular product design, repairability, and extended producer responsibility.

The model's ability to explain over half the variance in green economy alignment also speaks to the robustness of the proposed framework. Diagnostic tests support the reliability of the regression model, showing no violations of assumptions related to residual independence, multicollinearity, or normality. This strengthens confidence in the generalizability of the findings, despite the relatively small sample size. However, future studies could expand the sample to include firms from other regions or industrial sectors, as well as compare results across countries to examine how national policies shape the circular economy landscape.

Importantly, these results contribute to the broader discourse on sustainable development in transition economies. Serbian firms, particularly SMEs, often face barriers such as limited technical capacity and financial constraints. However, the study shows that even incremental adoption of circular practices can yield measurable alignment with green economic principles. For policymakers, this highlights the value of fostering ecosystems that encourage collaboration, knowledge exchange, and investment in circular infrastructure. Support mechanisms such as subsidies, training programs, and green procurement policies could amplify the impact of circular logistics at the national level

CONCLUSION

This study examined how circular supply chain practices contribute to achieving green economy goals within the Serbian manufacturing sector. Through the analysis of survey data from 32 manufacturing firms, it was found that recycling, product life extension, and reverse logistics are actively pursued to varying degrees, with recycling being the most widely implemented. The regression model confirmed that recycling and product life extension have a statistically significant positive influence on green economy alignment, while reverse logistics, although positively associated, did not achieve statistical significance.

The findings emphasize the importance of embedding circular practices into operational and strategic supply chain decisions. Companies that prioritize resource efficiency and product longevity are more likely to align with sustainability objectives and benefit from reputational, financial, and regulatory advantages. The evidence also suggests that there is untapped potential in reverse logistics, which, with adequate infrastructural support, could enhance environmental outcomes further.

The study contributes to the literature on circular economy and sustainable logistics by offering empirical validation of their interdependence in a transition economy context. It also provides actionable insights for both industry leaders and policymakers, underscoring the value of targeted support mechanisms to accelerate the shift toward circularity. Future research could expand on these findings by incorporating longitudinal data or cross-country comparisons to deepen understanding of the institutional and economic drivers of circular supply chain adoption.

REFERENCES

[1] O. P. Mishra, "Exploring performance of JIT supply chain in context of Indian industries," *IJAOM*, vol. 8, no. 4, p. 323, 2016, doi: 10.1504/IJAOM.2016.084151.

[2] Boško Josimović, M. Ilić, and L. Bezbradica, "A Methodological Approach to Selecting a Location for a Waste Disposal Terminal for Vessels on the Section of the Pan-European Waterway Corridor VII in the Republic of Serbia," *Energy and Environment Research*, vol. 6, p. 14, Nov. 2016, doi: 10.5539/EER.V6N2P14.

[3] A. Zhuravleva and A. Aminoff, "Emerging partnerships between non-profit organizations and companies in reverse supply chains: enabling valorization of post-use textile," *IJPDLM*, vol. 51, no. 9, pp. 978–998, Oct. 2021, doi: 10.1108/IJPDLM-12-2020-0410.

[4] E. Guevara-Rivera, R. Osorno-Hinojosa, and V. H. Zaldivar-Carrillo, "A Simulation Methodology for Circular Economy Implementation," in *2020 10th International Conference on Advanced Computer Information Technologies (ACIT)*, Deggendorf, Germany: IEEE, Sep. 2020, pp. 43–48. doi: 10.1109/ACIT49673.2020.9208839.

[5] G. Kokeza and S. Josipović, "Green transition of the textile industry: Opportunities and obstacles," *Tekstilna industrija*, vol. 71, no. 4, pp. 42–49, 2023, doi: 10.5937/tekstind2304042K.

[6] Dragan Milić, T. Novaković, Dragana Tekić, Bojan Matkovski, Danilo Đokić, and S. Zekić, "Economic Sustainability of the Milk and Dairy Supply Chain: Evidence from Serbia," *Sustainability*, Oct. 2023, doi: 10.3390/su152115234.

[7] S. Ugrinov, D. Ćoćkalo, M. Bakator, S. Stanisavljev, and M. Zakin, "Driving sustainable innovation in the textile industry through circular supply chain management," *Tekstilna industrija*, vol. 72, no. 2, pp. 36–47, 2024, doi: 10.5937/tekstind2402036U.

[8] M. Palazzo and A. Vollero, "A systematic literature review of food sustainable supply chain management (FSSCM): building blocks and research trends," *TQM*, vol. 34, no. 7, pp. 54–72, Dec. 2022, doi: 10.1108/TQM-10-2021-0300.

[9] G. A. R. García and Y. C. Rivas, "circular economy and environmental training as care of the common house," *ijls*, vol. 6, no. 1, pp. 1–9, Jan. 2022, doi: 10.53730/ijls.v6n1.3148.

[10] D. Zimon, P. Madzik, and R. Sroufe, "The Influence of ISO 9001 & ISO 14001 on Sustainable Supply Chain Management in the Textile Industry," *Sustainability*, vol. 12, no. 10, p. 4282, May 2020, doi: 10.3390/su12104282.

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QUALITY IN PROJECT MANAGEMENT AS A PIVOTAL PART IN THE CONSTRUCTION INDUSTRY

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Abstract: Effective project management is a critical determinant of project success, encompassing the systematic planning, coordination, and control of resources to achieve predefined objectives. It plays a pivotal role in ensuring that projects are delivered within the constraints of time, budget, and scope, while adhering to specified quality standards. In construction industry projects, quality management is particularly crucial, as the durability and reliability of the final product must align with established performance standards. A comprehensive quality management plan is integral to effective project execution. It delineates the quality benchmarks for each project phase and outlines procedures for testing, inspection, and compliance. This process involves not only evaluating tangible outputs, such as equipment, technical drawings, or specifications, but also validating, verifying, and documenting quality assurance and control activities throughout the project lifecycle.
Key words: Quality, project management, construction, engineering

INTRODUCTION

The primary phases of a project encompass planning, feasibility analysis, design, procurement, construction, acceptance, operation, and maintenance. Quality represents a crucial determinant of success in construction industry projects, reliant upon rigorous quality management implemented consistently throughout the entire project lifecycle. Among these phases, design and construction exert the most significant influence on the ultimate quality outcomes. Furthermore, construction quality can be conceptualized as the fulfillment of stakeholder expectations, achieved by maximizing participant satisfaction. Failure to meet these expectations often results in defective construction, which can lead to frequent and costly errors impacting both contractors and facility owners. Consequently, quality management has emerged as a vital strategic competitive advantage for numerous construction firms, underpinning product development and sustaining long-term organizational success.
Project management constitutes an indispensable element within the construction sector, characterized by projects of considerable scale and complexity that demand meticulous planning and execution [8]. Within this context, project planning and scheduling are paramount, as they directly influence the timely, budget-compliant, and quality-assured delivery of projects. Systematic and structured planning and scheduling processes are essential for mitigating prevalent industry challenges such as delays and budget overruns. Given the inherent complexity and unique obstacles of construction projects, well established planning frameworks are necessary to efficiently allocate resources, manage timelines, and align stakeholder expectations [12].

MATERIAL AND METHODS

This research aims to highlight the impact of production processes and human behavior on construction projects, with a focus on quality as a key component of project management. By examining a wide range of sources, including normative texts and case studies, the research is situated within a broader scientific and operational context. Key concepts are examined through a review of selected scientific literature on Quality, Project management, and Lean Six Sigma, with a focus on how these areas align with sustainability principles, construction practices, and organizational management. This analysis provides a critical evaluation of their applicability, effectiveness and potential areas for improvement. Fundamental concepts, such as quality control, risk, and opportunity, are explored through document review and content

analysis. A combination of deductive and inductive approaches is used to classify and synthesize the theoretical foundations of the research.

Understanding of Quality in Project Management

Defining quality

The concept of "quality" is frequently encountered in daily life, often appearing in various forms of advertising. Phrases such as "top quality," "quality suppliers," "quality first," and "the place where quality matters" are commonly used to emphasize the perceived excellence of products or services. The term "quality" is almost universally associated with positive connotations, making it a highly desirable attribute for companies to align themselves with. In contemporary organizational contexts, establishing a connection with the notion of quality is considered essential. However, the precise definition of "quality" and the processes involved in attaining it remain subjects of ongoing debate.

The responsibility for ensuring quality primarily rests with organizational management and achieving quality outcomes necessitates both managerial awareness and appropriate training.

Juran's work on Planning for Quality emphasizes the principle that "quality does not happen by chance, it must be planned," highlighting the necessity of deliberate efforts in quality management. This perspective forms a core element of his "Quality Trilogy," which comprises Quality Planning, Quality Control, and Quality Improvement [10].

Quality Management Plan

The Quality Management Plan serves as the primary document guiding quality-related activities within a project and functions as one of several subsidiary management plans under the broader project plan. Given that quality management is often perceived as a complex or unfamiliar task, project managers may seek existing templates as a starting point. However, such templates are scarce, and the project management literature tends to offer descriptive overviews of quality management plans rather than concrete examples, although these descriptions can still offer valuable insights. Relying solely on templates may constrain the thoughtful consideration required to address the specific characteristics of individual projects. Consequently, it is recommended that project teams develop a customized Quality Management Plan that reflects the unique requirements and context of their project. In recent years, the importance of planning has increased, largely due to the growing adoption of project-based structures within companies and the integration of diverse project types into broader project portfolios. As a result, business managers who may have limited formal experience in project management are increasingly assuming the role of project managers. This shift heightens the significance of effective planning and results in greater reliance on planning functions to support project execution and oversight [4].

Requirements for Quality Control

During the formulation of a construction plan, the designer bears a critical responsibility to guarantee that all aspects of the project are cost effective, precise, thoroughly developed, well coordinated, rigorously reviewed, and fully finalized. To reliably fulfill the demands and expectations of the public, the pursuit of quality must be regarded with equal importance to adherence to schedule and budget constraints [3].

Quality Control

Monitoring involves the systematic evaluation of project outcomes to verify their compliance with established quality standards, as well as the identification of underlying causes of performance deficiencies to enable corrective measures. Contract documents serve as a precise, comprehensive, and accurate representation of the facility to be constructed, effectively conveying the owner's expectations concerning the facility's intended features and functional purpose.

Contract documents establish that the facility to be constructed complies with relevant regulatory codes and professional standards. This includes ensuring the facility's reliability, maintainability, material and system durability and strength, as well as the level of life safety afforded to its users [7]. Quality is defined as the degree to which a product conforms to the specifications and standards set by the construction firm. Quality control is the process by which the construction work is verified to meet prescribed performance and durability requirements. This process encompasses all stages, from material procurement to the completion of construction. Critical quality control activities conducted before and during construction include the assessment of soil conditions, review of drawings and design documents, verification of structural integrity and durability, evaluation of material quality and compliance with specifications, material testing, and equipment inspection. Quality control encompasses multiple dimensions, including the testing of materials before installation, conducting both field and laboratory evaluations, and ensuring that personnel possess sufficient knowledge of the appropriate construction methods, techniques, necessary precautions, and testing frequencies. A fundamental aspect of this process is the verification that all materials intended for use in the project conform to the specified requirements [9]. Quality control is broadly defined as a systematic approach aimed at sustaining a predetermined level of quality through the continuous monitoring of product or service attributes and the implementation of corrective measures when deviations from established standards occur. This domain can be categorized into three primary subfields: off-line quality control, statistical process control, and acceptance sampling plans [5].
Monitoring specific project results serves several important purposes:

- Primarily, it provides validation that the project is progressing as intended. When outcomes align with established specifications, the project team can be assured that work activities are being executed in accordance with the project plan.
- Project results also serve as a foundation for initiating corrective measures. When outcomes deviate from specified requirements, it signals that an issue has arisen, prompting the project team to implement appropriate corrective actions to address the discrepancy. Moreover, the team needs to investigate and identify the root cause of the nonconformity and implement preventive measures to mitigate the risk of recurrence.
- Project results function as critical feedback on the effectiveness of the quality assurance process. Data gathered through quality control measures is systematically evaluated during quality audits. When performance falls short of established specifications, it indicates that existing quality assurance activities are not fulfilling their intended purpose. Given that the fundamental goal of quality assurance is to ensure consistent adherence to defined standards, any performance gap necessitates a thorough analysis of the data to identify underlying deficiencies. The project team must then refine quality assurance practices and revise the quality assurance plan accordingly [11]. This continuous improvement approach aligns closely with the "Maintain" principle, which is inherently connected to the broader concept of sustainability [13].

Change control, encompassing a wide range of activities, may be fully or partially overseen by the Project and Programme Support Office (PPSO). Consequently, effective project management necessitates systematic coordination and control of key functions by the project management team [16].

Quality Improvement

Quality improvement is not just an idea, it is driven by a series of practical imperatives that require companies to continuously improve the quality of their products or services.

- The principal objective is to enhance product quality and minimize instances of nonconformity. By delivering superior products and reducing defects, companies can significantly improve customer satisfaction, which subsequently contributes to a stronger reputation and heightened competitive positioning in the market.
- Products do not exist in isolation,, they are developed to fulfill defined customer needs and expectations. A central motivation for pursuing quality improvement is to enhance the value

delivered to customers through superior products. Improved product quality not only fosters greater customer satisfaction but also has the potential to drive repeat business from existing clients and attract new customers, thereby contributing to company growth and market expansion.

- Enhanced processes lead to greater operational efficiency by optimizing time utilization, reducing waste, and minimizing the occurrence of nonconformities.
- Evolving customer demands and expectations necessitate a continuous commitment to improvement. Such pressure from customers should be regarded as a positive and constructive force, as it prevents organizational complacency. In the absence of this external impetus, there is a risk of stagnation, which can result in being outpaced or surpassed by competitors offering more innovative and superior solutions.
- Enhancing quality can lead to cost reductions by increasing operational efficiency and minimizing waste or defects. These cost savings can be strategically leveraged to improve competitiveness, either by enabling price reductions or by offering greater value through increased product or service output at existing price levels.
- Global competition is an enduring and inescapable reality of contemporary business. Virtually all products and services are exposed to international competitive pressures, often from regions where lower labor costs provide a distinct pricing advantage. In such contexts, enhancing product quality serves as a critical strategy for maintaining competitiveness, enabling firms to differentiate their offerings and remain viable in markets dominated by low cost producers.
- The rapid advancement of new technologies necessitates ongoing adaptation while simultaneously creating opportunities for quality enhancement. To remain competitive and responsive to market demands, companies must embrace continuous improvement. This ongoing process of change enables the consistent refinement of products and services, thereby delivering greater value to customers.

Quality improvement is essential to the long-term viability of a business. As outlined in the preceding discussion, failure to address any of the identified factors can critically undermine organizational performance and potentially lead to business failure [11].



Figure 1. Deming's PDCA circle [1]

Within the context of construction project management, quality management serves as a foundational pillar, frequently representing the decisive factor between organizational success and failure [1, 17].

Quality Assurance

Quality assurance encompasses a broad range of activities within project management, including the identification and mitigation of risks, the resolution of issues, and adherence to established quality standards and procedures. It may also entail comprehensive project audits, wherein all aspects of a project are systematically evaluated for compliance and effectiveness [4].
Failures in quality management frequently result in significant delays and cost overruns, disrupting projects that otherwise appear to be progressing well. Such crises often erode the anticipated advantages of the project, revealing underlying vulnerabilities in quality control systems [9].
Responsibility for quality does not reside with a single individual, rather, it is a collective obligation shared by all personnel involved, directly or indirectly, in the delivery of a product or service. Consequently, there is a critical need for a structured system that ensures strict adherence to all established procedures and plans. This is the foundational purpose of the quality assurance function [5].
Total Quality Management (TQM) is structured around three core pillars: the customer, internal processes, and the workforce. As depicted in Figure 2, the model is underpinned by the company's vision, mission, and the active commitment of its leadership. When employees lack a clear understanding of the strategic direction of the company, they may pursue personal or departmental objectives that conflict with overarching organizational goals, inadvertently undermining performance. For instance, prioritizing output volume without regard for cost efficiency or quality standards exemplifies such misalignment [5].

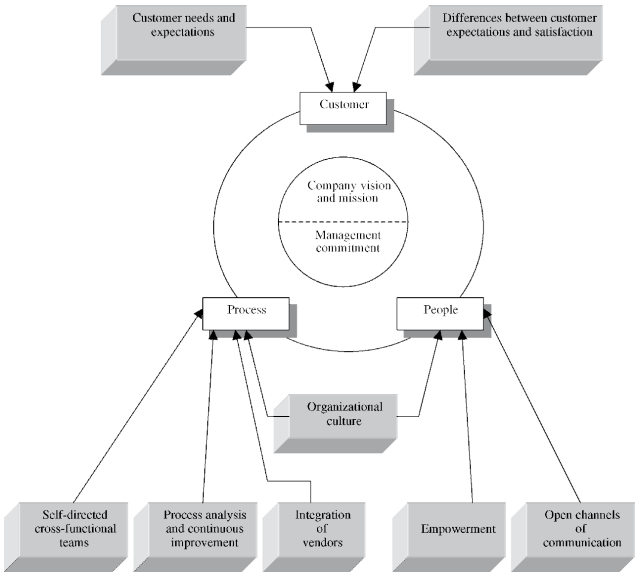


Figure 2: Features of a TQM model [5]

Risk management

Companies engaged in safety critical projects often adopt a rigorous approach to risk management, frequently employing dedicated risk management professionals whose primary responsibility is to support and oversee risk-related activities [4]. Risk management plays a pivotal role in project planning and scheduling due to the inherent and persistent uncertainties associated with construction projects. The systematic identification, analysis, and mitigation of risks are critical for minimizing potential disruptions and ensuring the continuity of project timelines [12].

Importance of Construction

A key determinant of construction quality is the accuracy, clarity, and completeness of the contract documents. Additionally, three other interrelated factors significantly impact construction outcomes: the competency of the workforce in executing specialized tasks, the presence of

experienced on-site supervisors who coordinate and oversee construction activities, and the quality and suitability of the materials employed in the building process [1]. Significant emphasis has been placed on the concept of Total Quality Management (TQM), a comprehensive organizational approach that necessitates collaborative effort across all hierarchical levels to enhance project quality and ensure optimal customer satisfaction. As a management philosophy, TQM is grounded in the principle of continuous process improvement, emphasizing the refinement of the systems and procedures involved in product development and delivery [1].

Lean Six Sigma Construction Principles

Lean principles are grounded in a systematic approach whereby companies identify and analyze all processes involved in converting raw materials into finished products in alignment with customer requirements. This analytical approach is commonly referred to as value stream mapping [13]. The concept of lean manufacturing was introduced in the 1980s by the International Automotive Project Group at the Massachusetts Institute of Technology, which examined innovative production strategies employed by Toyota in Japan. Since then, the notion of "lean thinking" has garnered considerable attention from both scholars and industry professionals [14]. In the context of construction, lean methodologies aim to enhance workflow efficiency, minimize non-value-adding activities, and improve overall project outcomes. The adoption of lean principles has been shown to result in substantial improvements in project performance, including reduced timelines and cost savings [12].
Companies that apply lean practices consistently seek to minimize the use of physical space, raw materials, water, energy, and equipment in their production processes [10]. Lean Six Sigma represents an integrated framework combining Lean Production and Six Sigma methodologies. It focuses on eliminating inefficiencies and non-value-added costs, minimizing process variation, and stabilizing the quality and performance of outputs, including those within the construction sector [15]. Quality management plans serve both internal and external functions for construction firms. They provide a structured means of ensuring compliance with predefined standards and regulatory requirements, thereby supporting the delivery of work that is both legally compliant and practically executable [2]. The variables that play a role in the successful implementation of a project are the risk of nonconformity of the construction, the complexity of the construction and the severity [6].

RESULTS AND DISCUSSION

Quality is commonly understood to be the extent to which a company fulfills the needs and expectations of its customers. The development, implementation, and continual enhancement of a quality management system (QMS) are critical to achieving this objective. An effectively designed and properly executed QMS ensures consistent delivery of products and services that conform to customer requirements. Beyond direct quality assurance, the implementation of a QMS yields significant indirect advantages, particularly in terms of cost efficiency. By minimizing the occurrence of nonconformities, such as defective products or rework resulting from unmet specifications, a QMS reduces waste, prevents operational delays, and promotes optimal time management. Overall, the systematic adoption of QMS is indispensable for organizational growth. It not only supports customer satisfaction but also contributes to enhanced operational performance and strengthens corporate reputation [3]. Quality assurance in construction projects requires focused and ongoing attention. The successful implementation of project activities relies heavily on having a skilled and competent workforce. Inadequate training among workers consistently results in subpar outcomes, as quality cannot be achieved without the necessary technical skills. Therefore, it is crucial to prioritize continuous professional development for both workers and supervisory staff through regular, targeted training programs designed to improve their operational abilities. This focus on training should also include supervisors and engineers, whose roles are vital in maintaining quality standards throughout the project lifespan. Ultimately, delivering high quality results in construction demands careful attention to all aspects of project management, including human resource development and capacity building.

CONCLUSION

Quality in project management is a fundamental pillar of success in the construction industry. It ensures that projects comply with technical specifications, meet client expectations, adhere to regulatory standards, and deliver long term performance, safety, durability, and functionality. Embedding quality management principles across all project phases, from planning and design to execution and handover, enhances efficiency, safety, sustainability, and client satisfaction.
Neglecting quality can result in costly rework, legal disputes, and reputational harm. In contrast, a strong focus on quality builds trust, adds value, and supports continuous improvement. In an industry as competitive and complex as construction, a commitment to quality is not optional, it is essential for delivering excellence and achieving long term success. By maintaining a quality first approach throughout the project lifecycle, risks are minimized, costs are reduced, and a reputation for excellence is established. In a field where trust and performance are critical, quality is not merely an added benefit, it is a strategic necessity for sustainability and lasting achievement.

REFERENCES

[1] Oberlender, G. D. (2000). *Project management for engineering and construction*. McGraw-Hill Higher Education, United States.
[2] Lester, A. (2006). *Project management: Planning and control*. Elsevier Science & Technology Books, United States.
[3] Rumane, A. R. (2017). *Quality management in construction projects*. CRC Press, Taylor & Francis Group, Boca Raton, FL.
[4] Cadle, J., & Yeates, D. (2008). *Project management for information systems* (5th ed.). Pearson Education Limited, Harlow, England.
[5] Mitra, A. (2016). *Fundamentals of quality control and improvement* (4th ed.). John Wiley & Sons, Hoboken, NJ.
[6] Meijer, F., & Visscher, H. (2017). Quality control of constructions: European trends and developments. *International Journal of Law in the Built Environment*, https://DOI: 10.1108/IJLBE-02-2017-0003.
[7] Bhattacharjee, J. (2018). Quality control and quality assurance in building construction. *International Research Journal of Management Science & Technology (IRJMST)*, ISSN 2250–1959.
[8] Mallawaarachchi, H., & Senaratne, S. (2015). Best practices in project planning: Insights from the Sri Lankan construction industry. In *Proceedings of the 6th International Conference on Structural Engineering and Construction Management*, Kandy, Sri Lanka.
[9] Salvi, S. S., & Kerkar, S. S. (2020). Quality assurance and quality control for project effectiveness in construction and management. *International Journal of Engineering Research & Technology (IJERT)*, ISSN 2278–0181.
[10] Watson, P., & Howarth, T. (2011). *Construction quality management: Principles and practice*. Spon Press, Abingdon, Oxon.
[11] Rose, K. H. (2005). *Project quality management: Why, what and how*. J. Ross Publishing, Boca Raton, FL.
[12] Oluwatosin, E. A. (2024). Best practices for efficient project planning and scheduling in construction management. *International Journal of Research Publication and Reviews*.
[13] Puvanasvaran, P., Kerk, R. S. T., & Vasu, S. A/L. (2014). Lean environmental management integration system for sustainability of ISO 14001:2004 standard implementation. Journal of Industrial Engineering and Management, 7(1), 134–157. https://doi.org/10.3926/jiem.907
[14] Jingkuang, L., & Guangsheng, S. (2017). Quality Control of a Complex Lean Construction Project Based on KanBIM Technology, Journal of Mathematics Science and Technology Education, DOI: 10.12973/eurasia.2017.01039a.

[15] Linde, I., & Philippov, D. (2020). Applying Lean Six Sigma in Construction. World Practice Experience, ACCESS Journal: Access to Science, Business, Innovation in Digital Economy, https://doi.org/10.46656/access.2020.1.2(2).
[16] Herath, S., & Chong, S. C. (2021). Key components and critical success factors for project management success: A literature review. Operations and Supply Chain Management: An International Journal, 14(4), 487–498. https://doi.org/10.31387/oscm0470314
[17] Pascal, D. (2015). Lean Production Simplified: A Plain-Language Guide to the World's Most Powerful Production System, CRC Press, Taylor & Francis Group, Boca Raton, Florida

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ENVIRONMENTAL AND ECONOMIC ADVANTAGES OF CIRCULAR GREEN WASTE MANAGEMENT

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Abstract: This paper examines the circular management of green waste as a crucial component of sustainable development, balancing environmental protection and economic efficiency. Through the analysis of the ecological and economic benefits of the circular economy, the paper emphasizes the importance of recycling, composting and reducing greenhouse gas emissions. Green waste is considered a valuable resource for producing compost and biogas, which can contribute to soil regeneration and biodiversity conservation, while simultaneously reducing pressure on landfills and extending their lifespan. In addition to environmental benefits, circular practices offer significant economic advantages, including reduced waste treatment costs and the creation of new markets for eco-friendly products. Case studies from European cities such as Vienna, Amsterdam and Stockholm show successful applications of circular practices in green waste management, while Serbia and other developing countries face challenges in implementing these practices, including lack of infrastructure, legislative barriers and low citizen awareness. The paper focuses on key challenges and recommendations for improving existing systems, including investment in infrastructure, development of the legislative framework and education of citizens. It also considers the potential for further development of circular practices in Serbia and other developing countries through innovation, international cooperation and financial incentives. The circular economy in green waste management can become the foundation for a more sustainable and economically efficient system, reducing the ecological footprint and opening opportunities for the development of new markets and jobs.
Key words:circular economy, green waste, recycling, composting, biogas, environmental benefits, economic benefits, sustainable development.

INTRODUCTION

In modern society, waste management represents one of the key challenges in the context of sustainable development. With the constant increase in urbanization and the intensification of industrial production, the amount of waste produced in large cities, as well as globally, is continually growing. A particularly significant part of this problem is green waste, which consists of plant material, such as plant remains, grass, leaves, branches, and other biological waste [1]. Although often perceived as a "lighter" type of waste, green waste has the potential to cause serious environmental and economic problems if not treated effectively. Depositing green waste without processing can lead to the creation of methane, a gas with a greenhouse effect, which significantly contributes to global warming [2]. Given these challenges, effective management and treatment of green waste becomes imperative to reduce its negative impact on the environment [3]. The circular economy, which is based on the principle of a closed loop of resources, represents an innovative approach to solving the problem of waste, including green waste. This concept opposes the traditional linear model of production and consumption, which implies "take, use, throw away" [4]. Instead, the circular economy strives to conserve resources through reuse, recycling and waste reduction. In the context of green waste, the circular approach implies its conversion into useful products, such as compost, biogas, or energy, thereby reducing the need for landfill and contributing to ecosystem sustainability [5]. One of the key goals of the circular economy in the treatment of green waste is not only the reduction of its negative impact on the environment, but also the creation of new economic value. By using innovative methods such as composting, anaerobic digestion or biogas production, green waste can be turned into useful resources that have commercial value.

Recycling green waste not only contributes to the conservation of natural resources but also reduces the emission of greenhouse gases, thereby reducing global warming [6]. The ecological benefits of applying circular practices in green waste management include reducing the amount of waste in landfills, reducing the emission of methane and other harmful gases, as well as enriching the soil with compost that improves its quality and fertility [7]. Economic benefits, on the other hand, can be realized through the reduction of waste processing and disposal costs, as well as through the commercial use of recycled materials, which contributes to the development of new green markets and business models [8]. Also, such an approach can contribute to the creation of new jobs in industries related to recycling and biogas production, which is particularly reflected in the development of local communities [9].
This paper explores the environmental and economic benefits that can be realized by implementing circular practices in green waste management, analyzing the impact of recycling and composting on reducing harmful gas emissions, as well as the long-term benefits for the economy and the environment. Understanding these aspects has a key role in guiding future waste management policy and strategy, not only at the global, but also at the national and local levels.

MATERIAL AND METHODS

Theoretical framework

Definition and basic principles of the circular economy

The circular economy (CE) is an economic model based on the principle of "closed loop", in which resources, products and materials remain in the economy as long as possible. This approach opposes the traditional linear model of production and consumption, which is based on the "take, use, throw away" model. A circular economy, on the other hand, tends to eliminate waste, maximize the use of resources, and encourage reuse, recycling, and regeneration of products and materials [4]. Key principles of the circular economy include:
1. Sustainable product design - products are designed in a way that allows long-term use, easy repair, recycling and reuse.
2. Reuse and recycling - instead of disposing of waste materials, they are reused or recycled into new products.
3. Disintegration into nature - use of materials that are environmentally friendly and can be decomposed naturally.
4. Sharing and redistribution - promoting a model of sharing resources and products that can be used by multiple users, thus reducing the need for new products [10].
The circular economy creates new value by minimizing the need to extract new resources and reducing negative environmental impacts, while at the same time contributing to economic development through innovation and green technology.
Overview of existing research and global initiatives related to circular green waste management
Green waste, which consists of plant residues, leaves, grass, branches and other plant materials, has the potential to become a significant resource if treated according to the principles of the circular economy. Globally, many countries and cities are implementing strategies for efficient green waste management, with the aim of reducing greenhouse gas emissions and reducing pressure on landfills. According to research, circular practices in green waste management can significantly contribute to the reduction of methane emissions, which are created in landfills, as well as to the increase of resource efficiency through composting and biogas production [8]. Case studies, such as the Vienna and Amsterdam programs, demonstrate how circular approaches can enhance green waste management. In Vienna, more than 40% of all municipal waste is recycled. The city has implemented a system for collecting and composting green waste, thereby reducing pressure on landfills and creating high-quality compost for agricultural use [11]. Similar programs in Amsterdam use green waste to produce biogas that is later used to generate energy [5]. Global initiatives, such as the Global Waste Management Outlook organized by UNEP (United Nations Environment Programme), encourage countries to focus on circular waste management, including green waste. The

European Union also provides guidance on waste management through various regulations and directives that promote a circular economy, such as the Circular Economy Action Plan [2].

RESULTS AND DISCUSSION

Overview of existing legislative frameworks in the EU, Serbia and other relevant countries

In the European Union, the legislative frameworks governing waste management largely support the principles of the circular economy. In 2020, the European Commission adopted the Circular Economy Action Plan, which includes specific measures for municipal waste reduction, recycling, and reuse of materials, and green waste is recognized as a key element in achieving these goals. Directives such as the Waste Framework Directive (2008/98/EC) and the Landfill Directive (1999/31/EC) call on member states to develop systems to reduce landfilling and increase recycling [2]. In Serbia, the legislative framework for waste management includes the Law on Waste Management, which is aligned with European regulations, but there are also challenges in implementation. There are initiatives to improve recycling and composting, but the green waste management system is still underdeveloped. In some cities in Serbia, such as Belgrade and Novi Sad, there are pilot projects promoting composting and recycling of green waste, while existing laws still do not fully recognize the economic potential of this industry [12]. In many developed countries, such as Sweden, the Netherlands, and Denmark, waste legislation is much more rigorous and includes economic incentives for recycling and landfill reduction. For example, Denmark has implemented tax breaks for companies that use recycled materials, while Sweden uses advanced technologies to produce energy from green waste [9].

Environmental benefits of circular green waste management

Reducing greenhouse gas emissions through recycling and composting green waste

One of the most important environmental aspects of circular green waste management is the reduction of greenhouse gas emissions, especially methane (CH_4). Methane is one of the most harmful greenhouse gases, with a global warming potential that is 28 times more potent than carbon dioxide over 100 years [6]. Through proper green waste management, recycling, and composting, this green waste can be converted into useful resources, and methane emissions are significantly reduced. Composting is a particularly efficient process because it allows for the aerobic decomposition of plant material, which reduces the generation of methane that is produced under anaerobic conditions, such as in landfills. In European countries such as Germany and the Netherlands, the implementation of green waste collection and composting systems has reduced methane emissions from landfills by more than 20% [8]. Research also shows that composting can contribute to reducing carbon dioxide emissions in the soil, as composting helps to fix carbon dioxide in the soil, thereby reducing its negative impact on the atmosphere [7].

The role of green waste in soil regeneration and biodiversity conservation (composting, mulching)

Green waste plays a key role in soil regeneration, improving soil fertility and preserving biodiversity. Composting and mulching, the two main processes for treating green waste, have numerous environmental benefits, especially in agriculture and urban areas.

Composting enriches the soil with nutrients and microorganisms, improving its structure and moisture. Due to its high organic matter content, compost helps improve soil drainage, reduces erosion and increases the soil's water-holding capacity, which is especially important in areas with dry periods [1]. Compost is also rich in nitrogen, phosphorus and potassium, making it extremely useful for improving soil fertility, thus reducing the need for the use of artificial fertilizers, which can be harmful to the environment [5].

Mulching, which is often used as a way to treat green waste, has similar benefits. This process involves placing a layer of organic material, such as grass clippings or leaves, on the soil surface. Mulch helps reduce evaporation, suppresses weed growth, improves soil structure,

and helps conserve moisture in dry conditions. The use of mulch in urban areas can also contribute to the preservation of biodiversity, as it increases the number of plant and animal species that can survive in such an environment [11]. In addition, composting and mulching reduce the need for chemical pesticides and fertilizers, which directly affects the preservation of biodiversity. Reduced use of chemicals makes the soil more suitable for plants, microorganisms, and insects, thereby contributing to the preservation of the local ecosystem [4].

Reducing landfill burden and extending their lifespan

Landfills pose a major environmental challenge, as they occupy large areas of land and cause significant pollution, including the emission of greenhouse gases such as methane. One of the key objectives of circular green waste management is to reduce the amount of waste going to landfills, thereby extending their lifespan and reducing the need to build new landfills. According to the European Commission, green waste makes up a significant portion of the total municipal waste generated in cities. By recycling and composting green waste, landfill capacity is drastically reduced. In Belgium, for example, by implementing a system for collecting green waste and processing it into compost, the landfill burden was reduced by 25% [3]. Reducing the landfilling of green waste not only helps reduce the burden on landfills, but also contributes to reducing emissions of pollutants, such as heavy metals and toxins that are produced by the decomposition of waste in landfills [9]. By using technologies such as biogas, which can be produced from green waste, it is possible to create renewable energy sources and further reduce the need for fossil fuels [5].

Economic advantages of circular green waste management

Business models based on the circular economy: how businesses can profit from recycling green waste (e.g. selling compost, biogas)

The circular economy not only contributes to environmental protection but also creates new economic opportunities for companies that implement business models based on the recycling and reuse of resources. Businesses can profit by selling products obtained by recycling green waste, such as compost and biogas.

Composting green waste creates high-value products for agriculture, such as organic composts that improve soil quality and reduce the need for artificial fertilizers. In the EU, the compost market is growing, with recognizable businesses selling compost for agricultural and horticultural use [3]. Composting businesses can make a profit through direct sales of compost or in the long term through partnerships with farmers who are looking for sustainable alternatives to traditional fertilizers. In addition, biogas produced from green waste can be a source of renewable energy, allowing businesses to profit through the sale of energy or biogas. In addition, biogas produced from green waste can be a source of renewable energy, allowing businesses to profit through the sale of energy or biogas. Biogas production not only enables energy savings but also contributes to reducing dependence on fossil fuels. For example, Denmark has established successful models for the production of biogas from green waste, which has enabled the sustainable growth of the sector [5].

Savings through reduced landfill costs and lower waste treatment costs

One of the key economic benefits of the circular management of green waste is the reduction of disposal costs and the reduction of waste processing costs. Landfills are expensive to build and maintain, and in many cases pose a risk of soil and groundwater pollution. By implementing circular practices, such as green waste recycling, the amount of waste that ends up in landfills can be reduced, which directly reduces disposal costs and long-term landfill remediation costs. According to an OECD report (2018), waste management through circular practices can reduce landfill and recycling costs by up to 30%, thereby increasing the cost-effectiveness of the entire waste management system. In addition, by recycling green waste, companies can reduce the need to purchase new resources, which further reduces production and transportation costs. For example, cities such as Vienna use composting processes that reduce pressure on landfills and enable further investment in infrastructure projects [11]. These

savings not only help businesses reduce operating costs, but also support sustainability through resource optimization and pollution reduction.

Application of economic instruments (subsidies, tax breaks, ecological certificates) to encourage circular practices

In order to encourage the implementation of circular practices, governments and international organizations use economic instruments such as subsidies, tax breaks and environmental certificates. These instruments make it possible to reduce the initial costs for companies investing in green waste recycling and reuse technologies, which motivates them to engage in the circular economy. For example, subsidies for green waste processing companies can reduce the initial investment in infrastructure required for composting or biogas production. In some EU countries, biogas production projects are subsidized, thus encouraging companies to develop technology for the collection and recycling of green waste [2]. Also, tax breaks can encourage businesses to invest in sustainable practices, such as composting or using environmentally friendly materials, thereby reducing their environmental footprint. In many European countries, businesses implementing a circular economy can receive tax credits for using recycled materials or technologies that reduce pollutant emissions. Environmental certificates such as ISO 14001 or specialized certificates for recycled products allow companies to demonstrate their commitment to sustainability, which can improve their market position. Consumers and business partners are increasingly favoring companies that practice circular practices, thus opening up the market for "green" products. These economic instruments not only support companies in their efforts towards sustainability, but also create an incentive for the wider application of circular models in industries around the world [9].

Case studies

Case studies: Analysis of successful circular economy applications in green waste management

1. Global perspective and analysis of successful circular economy applications in European and global cities

The circular economy is becoming a key component of global strategies for reducing CO2 emissions, regenerating resources and restoring ecosystems. Green waste management, which constitutes a significant part of municipal waste, has an important role in this process. Cities around the world are recognizing the importance of recycling and composting green waste, implementing innovative technologies that not only reduce pressure on landfills, but also contribute to sustainable energy production and agriculture. Vienna stands out as a leader in the application of the circular economy, intending to recycle 60% of its municipal waste, including green waste, by 2025. The city currently recycles 45-50% of green waste, while the rest is used to produce biogas and compost. Vienna uses recycled green waste to produce energy and organic fertilizers, which contributes to reducing CO2 emissions [13]. Similarly, Amsterdam is implementing composting and biogas systems from green waste, achieving 50% recycling of municipal waste. The city plans to increase this rate to 65% by 2030, which will significantly reduce the burden on landfills and improve the circular model of waste management [14]. In Stockholm, the green waste recycling system includes the production of biogas, which is used for heating and electricity generation. Sweden has achieved recycling of 48% of municipal waste, including green waste, and plans further growth to 50-55% by 2030, which is part of a strategy to reduce CO2 emissions [15].

Table 1. *Ways to decrease green waste*

City	Percentage of recycled green waste (%)	Technologies in use	Goals by 2030.
Vienna	45-50%	Composting, biogas, energy	60%
Amsterdam	50%	Composting, biogas	65%
Stockholm	48%	Biogas, energy	50-55%

Source:City of Vienna (2020). Waste Management and Circular Economy in Vienna. https://www.wien.gv.at; Amsterdam City Council (2020). Circular Economy in Amsterdam. https://www.amsterdam.nl; Stockholm Environmental Department (2020). Sustainable Waste Management in Stockholm. https://www.stockholm.se.

Global trends in green waste management

Global statistics show that many developed countries are making significant progress in recycling green waste. For example, the United States recycles about 35-40% of green waste, while China, the largest producer of green waste, only recycles 30% of green waste. On the other hand, Japan achieves an impressive 70-80% recycling rate, setting the standard for global green waste management initiatives [16].

Table 2. *Global trends in green waste management*

Country	Percentage of recycled green waste (%)	Year
EU (averadge)	40-50%	2020
USA	35-40%	2020
China	30%	2020
Japan	70-80%	2020

Source: United Nations Environment Programme (2018). Global Waste Management Outlook. https://www.unenvironment.org/resources/report/global-waste-management-outlook

Application of circular practices in Serbia

In Serbia, the circular economy in green waste management is still in the development phase, but there are initiatives in several cities. For example, Belgrade has started selective collection of green waste, while Niš and Kragujevac are working on implementing composting. Although there is progress, challenges such as lack of infrastructure, lack of standardized practices and insufficient investment in technology still hinder further development. Belgrade plans to expand the system for collecting green waste, and there are also initiatives to introduce biogas plants in the city's surroundings. Also, Niš and Kragujevac are working on pilot projects for composting, but the results are still not significantly visible. However, there is a growing interest in investing in sustainable practices and environmental projects, which could significantly improve green waste management in the future [17].

Table 3. *Circular practices in Serbia*

City/Region	Implementation of circular practices	Achieved goals	Challenges
Belgrade	Composting, biogas, selective collection	10-15% recycled green waste	Lack of infrastructure and investment
Niš	Composting, education of citizens	Initial goals set	Financial resources
Kragujevac	Composting, development of public system	Projects related to green waste at the beginning	Poor institutional support

Source: Ministry of Environmental Protection of the Republic of Serbia (2020). Plan for waste management in Serbia. https://www.ekologija.gov.rs.

The role of local communities and the private sector in the implementation of the system
Local communities and the private sector play a key role in implementing circular green waste management systems. Local authorities encourage citizens to separate green waste, and private companies can contribute to the development of technologies for biogas, compost and markets for ecological products.
In cities such as Vienna and Stockholm, private companies are collaborating with local authorities to efficiently produce biogas and compost. In Serbia, the private sector, although in the development phase, can become a key actor in improving the infrastructure for green waste management. Private companies can play a key role in introducing innovative technologies, while local authorities can provide financial support through subsidies and tax breaks.

Table 4. *The local community role*

Type of Actor	Role in implementation	Example
Local authorities	Encouraging citizens to recycle, waste separation, and education	Vienna and Stockholm
Private sector	Development of technologies for biogas, compost, and the product market	Waste management companies (Austria, Sweden)
Public institutions	Development of policies, regulations, and financial support	EU subsidies, tax breaks

Source: European Commission (2020). Circular Economy Action Plan. https://ec.europa.eu/environment/circular-economy

Green waste management through the circular economy is a key component of sustainable development, both at the global and local levels. Global cities such as Vienna, Amsterdam and Stockholm are setting high standards in implementing circular practices, demonstrating that effective green waste management can lead to significant environmental and economic benefits. These practices reduce greenhouse gas emissions, increase renewable energy production through biogas, and contribute to soil regeneration through composting. Also, they reduce the load on landfills, thus extending their lifespan. Considering these successful examples, it can be concluded that the circular economy provides a unique opportunity for the transformation of waste management and the reduction of negative environmental effects. In Serbia, although there are initiatives at the local level, there are still numerous challenges in terms of infrastructure, institutional support and education of citizens. However, with appropriate investments in technologies and wider application of ecological practices, it is possible to significantly improve green waste management and contribute to the sustainable development of the country. Further development of circular systems in Serbia will depend on the integration of the private sector, local authorities, and citizens, who, through cooperation, could create a more sustainable and economically profitable waste management model.

Challenges and recommendations in the implementation of the circular economy in green waste management
1. The main challenges in implementing the circular economy in Serbia and other countries
The implementation of the circular economy in green waste management faces numerous challenges, which vary from technical and infrastructural to legislative and social obstacles. In Serbia, but also in many other developing countries, these challenges represent a significant burden on the way to sustainable waste management.
Infrastructure obstacles: The biggest challenge in Serbia and many other countries is the lack of developed infrastructure for the collection, transport and processing of green waste. Many local communities still do not have adequate systems for the selective collection of green waste, and existing landfills are not equipped to process organic waste in a sustainable manner. Also, in some countries, there is a lack of biogas plants, composting plants and other facilities that enable the recycling of green waste into useful products.

Legislative and institutional framework: The lack of consistent and effective laws regulating green waste recycling is one of the biggest challenges. Although there are basic laws on waste management, many countries, including Serbia, do not have specific laws that would encourage the recycling of green waste and oblige cities and companies to implement circular practices. Also, there is a lack of coordination between institutions, which slows down the development of systems for sustainable waste management.

Financial challenges: Many cities, especially in developing countries, face significant financial challenges. There is a lack of public and private investment in the infrastructure and technology required for effective green waste management. Without adequate financial resources, the implementation of circular practices remains limited.

Education and awareness of citizens: Another key challenge is the low awareness of citizens about the importance of recycling and circular practices. Many people are not sufficiently informed about how to properly separate green waste, which leads to its improper processing and reduces the efficiency of the recycling system. Additional investments in education and awareness campaigns among citizens are needed.

2.Proposals for improving existing systems and improving policies and regulations

In order to overcome the challenges in the implementation of the circular economy, it is necessary to develop a comprehensive approach that includes improvements in infrastructure, legislation, education and financial policies. Some of the key suggestions for improving the green waste management system include:

Developing infrastructure for green waste management: For the successful implementation of circular practices, investment in infrastructure for selective collection, transport and processing of green waste is necessary. This includes the construction of biogas plants, composting plants, as well as the modernization of landfills in order to enable the processing of green waste in an environmentally friendly manner. Investments in such systems would enable Serbia and other countries to recognize the potential for the production of compost and biogas as renewable energy sources.

Strengthening legislative frameworks: It is necessary to develop specific laws that regulate the recycling of green waste and oblige cities and companies to implement circular practices. Legislative initiatives should include subsidies for companies investing in circular technologies, tax breaks for citizens who separate waste, and stricter penalties for improper waste management. Also, it is important to harmonize the legislative framework with the European Union in order to ensure continuity in the EU integration process.

Financial support and incentives: In order to provide the necessary funds for infrastructure development, it is necessary to introduce financial incentives, subsidies and tax breaks for companies dealing with green waste processing. Also, international financial assistance and partnerships with the private sector can significantly contribute to the development of these technologies and practices.

Education and awareness raising of citizens: Investing in education and awareness-raising campaigns among citizens is a key element for the successful implementation of circular practices. Educational programs in schools, information campaigns through the media, and organizing local events can help promote proper green waste management. Also, it is important to involve citizens in the creation of policies and decisions related to waste management in order to increase their involvement.

Possibilities for further development of circular practices and technologies in green waste management

To further develop circular practices in green waste management, it is necessary to research and implement new technologies and approaches that can improve efficiency and economic benefits.

Technological innovations in green waste recycling: Technologies such as closed system composting, biological treatment and aerobic digesters can significantly improve the efficiency of the green waste recycling process. Also, the introduction of smart waste monitoring and management systems, such as sensors to identify waste types and track them via the Internet (IoT), can help in more efficient collection and recycling.

Development of compost and biogas markets: Markets for products made from recycled green waste, such as compost and biogas, need to be developed. These technologies can contribute not only to the reduction of CO2 emissions, but also to provide renewable energy sources and ecological products that can be used in agriculture, horticulture and energy. Developing a biogas market can also contribute to reducing dependence on fossil fuels.
International cooperation and exchange of experience: Serbia and other developing countries can learn from the experiences of developed countries, such as Germany, Sweden and the Netherlands, which have implemented successful green waste management systems. International cooperation, exchange of experiences and joint projects can help in faster adaptation and application of circular practices, as well as in providing the necessary funds and technologies. The implementation of the circular economy in Serbia and other countries faces significant challenges, but there are also numerous opportunities to improve existing systems. Key steps towards successful implementation include strengthening the legislative framework, investing in infrastructure, improving education and raising awareness among citizens, as well as providing financial incentives for businesses and institutions. Further development of circular practices, with the support of innovation and international cooperation, can enable Serbia and other countries to achieve sustainable development goals and reduce the negative environmental effects of green waste management.

CONCLUSION

Circular green waste management is a key component of sustainable development, both at the global and local levels. Through efficient processing of green waste, such as composting and recycling, it is possible to reduce greenhouse gas emissions, regenerate soil, preserve biodiversity and extend the life of landfills. The ecological advantages of the circular economy in green waste management are not only important for environmental protection, but also for reducing waste processing costs, which has a significant economic impact.
In EU countries, such as Germany, Sweden and the Netherlands, the implementation of circular practices has shown successful results in reducing the amount of waste in landfills, producing renewable energy sources through biogas and increasing the efficiency of recycling. Globally, cities such as Vienna, Amsterdam and Stockholm are setting high standards for green waste management, providing valuable examples for developing countries such as Serbia. Although there are numerous challenges, such as a lack of infrastructure, low awareness of citizens and a weak legislative framework, the potential for the application of circular practices in Serbia is significant.
For the further development of circular practices in Serbia, it is necessary to invest in infrastructure, improve legislative frameworks and provide financial incentives for companies dealing with green waste recycling. Also, educating and raising citizens' awareness of the importance of proper waste management is key to achieving sustainability goals. The application of circular practices can open new markets for compost, biogas and other products generated from green waste, thus contributing to economic growth and employment. Although there are challenges in the implementation of circular practices in Serbia and other developing countries, given the available technologies, international cooperation and political will, there is great potential for improving existing systems. Further development of circular practices will not only contribute to reducing the ecological footprint, but will also create the foundations for a more sustainable and economically efficient waste management system. By directing resources towards sustainable development, the circular economy can become a key driver of innovation, employment and environmental protection.

REFERENCES

[1] Keesman, K. J. Management of green waste in urban environments: Challenges and opportunities. *Waste Management and Research*, Vol.35, No.9, pp.1023-1032, 2017.
[2] European Commission, 2020. Circular economy action plan: For a cleaner and more competitive Europe. Avaliable at:https://ec.europa.eu/environment/circular-economy
[3] Sullivan, K. Addressing the challenges of green waste management in large cities. *Environmental Research Letters*, Vol.14, No.10, pp.104023, 2019.
[4] Ellen MacArthur Foundation, 2017. Circular economy: A transformative economic model for a sustainable future. Avaliable at: https://www.ellenmacarthurfoundation.org/circular-economy
[5] Bocken, N. M. P. Circular economy: Reviewing its possibilities and challenges for the management of waste and resources. Journal of Cleaner Production, Vol.257, pp.120434, 2020.
[6] IPCC, 2019. Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. Intergovernmental Panel on Climate Change.Avaliableat SRCCL-Full-Report-Compiled-191128.pdf
[7] Gillingham, K., & Parkinson, T. Environmental benefits of composting green waste in urban areas. *Waste Management*, Vol.72, pp.115-121, 2018.
[8] Lieder, M., & Rashid, A. Circular economy business models: Implementation and the role of green technology in waste management. *Resources, Conservation & Recycling*, Vol.156, pp.104676, 2020.
[9] OECD, 2018. The circular economy in cities: A review of the OECD study. Organisation for Economic Co-operation and Development. Availableat https://www.oecd.org/environment/waste/
[10] Stahel, W. R. The performance economy.Palgrave Macmillan UK, 2010, ISBN 1349283584, 9781349283583
[11] Schmidt, L. Urban green waste management and circular economy in Vienna. *Waste Management*, Vol. 82, pp.171-180, 2019.
[12] Ministry of Environmental Protection of the Republic of Serbia, 2019. Waste management Law. Avaliableat https://www.parlament.gov.rs
[13] City of Vienna, 2020. Waste Management and Circular Economy in Vienna. Avaliable at: https://www.wien.gv.at
[14] Amsterdam City Council, 2020. Circular Economy in Amsterdam. Avaliable at: https://www.amsterdam.nl
[15] Stockholm Environmental Department, 2020. Sustainable Waste Management in Stockholm. Avaliableat https://www.stockholm.se
[16] United Nations Environment Programme, 2018. Global Waste Management Outlook. Avaliableat https://www.unenvironment.org/resources/report/global-waste-management-outlook
[17] Ministry of Environmental Protection of the Republic of Serbia, 2020. Plan for waste management in Serbia. Avaliableat https://www.ekologija.gov.rs.

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POTENTIAL FOR RDF PRODUCTION IN REPUBLIC OF SERBIA

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Abstract: Waste management plays a central role in the transition to a circular economy by closing material cycles, recovering energy from non-recyclable fractions, and reducing emissions through safe treatment and disposal. In the European Union, recycling rates have increased and landfilling decreased, yet municipal solid waste which represents around 27% of total waste generated—continues to grow in both quantity and heterogeneity, posing risks to health and the environment. Energy recovery from MSW is increasingly recognized as essential for achieving EU goals on reducing energy dependence and mitigating climate change, with technologies such as anaerobic digestion, incineration, gasification, pyrolysis, and mechanical-biological treatment producing fuels like refuse-derived fuel and solid recovered fuel. Despite the challenges of complex waste composition, MSW has considerable calorific value, particularly from plastics, paper, textiles, and wood, making it a significant resource for energy production.
Key words: waste, production, fuel, energy, recovery.

INTRODUCTION

Serbia, a South-Eastern European country and candidate for European Union membership since 2014, encompasses a territory of 77,474 km² and has a population of approximately 6.7 million. Waste management represents one of the key environmental challenges in the country, particularly in the field of municipal solid waste (MSW). The collection of MSW in Serbia remains largely based on mixed waste streams, with limited implementation of primary separation practices. Separate collection is most applied to polyethylene terephthalate (PET) and paper and is concentrated in more developed urban areas. Waste collection services are predominantly provided by municipal public enterprises. Recycling performance in Serbia remains low, with the overall recycling rate amounting to 15.5% in 2020, while less than 2% of recycled materials originated from households [1]. These figures underline the structural weaknesses of the current system and highlight the urgent need to strengthen source separation, enhance recycling capacities, and accelerate the development of sustainable waste management practices in line with EU directives and circular economy objectives.

WASTE TO ENERGY POTENTIAL

Waste-to-Energy Potential in Europe and Beyond

Thermal treatment technologies, including incineration, pyrolysis, gasification, mechanical-biological treatment, and biological drying, are widely applied to transform municipal solid waste (MSW) into refuse-derived fuel (RDF) and solid recovered fuel (SRF). In the European Union, waste-to-energy (WtE) plants account for approximately 2.9% of the total electricity generated from renewable energy sources [2].
Within the EU-25, the energy embedded in industrial waste suitable for co-processing already meets around 40% of the demand of energy-intensive industries, with projections suggesting this share could rise to nearly 50% by 2030 [3].

In 2019 alone, European WtE facilities produced primary energy equivalent to 13.8 billion cubic meters of natural gas, which corresponds to roughly 9–10% of the EU's total gas imports. On a global scale, municipal solid waste generation amounts to nearly 2 billion tonnes annually, equivalent to approximately 2.247 × 10^15 kJ of energy. Integrated thermal WtE systems can reduce waste volumes by up to 90%, while achieving overall energy efficiencies as high as 60%, particularly when advanced processes such as plasma gasification are applied [4]. At the EU level, system-wide optimization of WtE operations has the potential to increase annual energy recovery from approximately 672 PJ to 872 PJ, representing a 29% improvement through more efficient utilization of existing waste streams.

Waste-to-Energy Development in Serbia

As part of its broader efforts to modernize waste management and harmonize with European Union standards, Serbia has initiated projects to establish controlled waste incineration and energy recovery facilities. A large-scale plant is under construction in Belgrade, while additional facilities are planned for Niš and Kragujevac. These plants are designed to process non-recyclable municipal waste and generate both electricity and heat, thereby reducing reliance on landfilling and supporting diversification of the national energy mix.

Alongside these initiatives, the cement industry has played a prominent role in energy recovery through co-incineration. Cement plants in Beočin and Novi Popovac are already licensed to use alternative fuels such as refuse-derived fuel (RDF), waste tires, and hazardous waste fractions in their kilns, substituting a portion of conventional fossil fuels. This demonstrates the increasing integration of industrial co-processing into Serbia's waste management framework. Plans set out in the Waste Management Program for 2022–2031 envision the establishment of regional RDF production facilities and specialized treatment plants for industrial and medical waste. These developments point to a gradual but meaningful transition towards waste-to-energy solutions, supporting Serbia's long-term goals of reducing landfill dependence, strengthening energy recovery, and aligning with EU climate and circular economy objectives [5].

RDF and SRF production and utilization

Within the European Union, RDF and SRF are increasingly recognized as important substitutes for fossil fuels, particularly in energy-intensive sectors such as the cement industry. Their use contributes both to waste management and to lowering greenhouse gas emissions by diverting waste away from landfills and replacing conventional fuels like coal and petroleum coke [6]. Globally, markets for RDF and SRF are expanding steadily, driven by their role in supporting decarbonization efforts and compliance with climate policies such as the EU Emissions Trading System. Life-cycle studies suggest that, although their production generates some emissions, these are outweighed by the environmental benefits associated with reducing landfill dependency and fossil fuel use. Despite these advantages, the potential of RDF and SRF in Europe has not yet been fully realized, as current generation and uptake remain below what could be achieved. This indicates considerable room for growth, both in terms of increasing the share of waste converted into RDF/SRF and in expanding their application across industries seeking low-carbon energy alternatives.

ASSESMENT OF THE WASTE POTENTIAL FOR RDF PRODUCTION ON THE STATE LEVEL

According to the most recent data published by the Serbian Environmental Protection Agency (SEPA), the total amount of MSW generated in 2023 reached 3.1 million tons, of which nearly 80% (2.46 million tons) was disposed of in landfills. The national waste management system is currently structured into 27 waste management regions, each intended to serve municipalities with more than 200,000 inhabitants and organized around regional sanitary landfills and associated infrastructure. Despite this framework, only 10 regional sanitary landfills are operational at present.

The separate collection will be improved soon, and the projected quantities of separately collected fractions of municipal waste amount up to 800.000 tons in 2024. The following diagram shows the average morphological composition of municipal waste for the Republic of Serbia. Fractions of municipal waste with potential for RDF production include plastic, paper and cardboard, textile, diapers, bulky waste and other small fractions of municipal waste.

Table 1. *Potential of municipal waste for RDF production at the state level*

Waste fraction	%	tons/year
Residues from Plastic	11%	99.544,3
Residues from Paper	9%	75.097,3
Textile	15%	130.665,0
Diapers	13%	116.896,0
Others	38%	329.894,0
Bulky waste	13.94%	121.794,0
Total	**100%**	**873.890,5**
Percentage of recovery/Total		**31%**

Based on the average morphological composition of mixed municipal waste in Serbia and the projected quantity of municipal waste that will be generated in Serbia in 2024 (assuming that 25% of the total waste is residual waste), potential for RDF production was calculated. It is estimated that the total theoretical potential for RDF production is approximately around 873.890 tons/year from municipal waste.
From total potential for RDF production from municipal solid waste, 59.758,72 tons/year are communal packaging waste collected within EPR system (Table 3), so the total potential for RDF production from municipal waste is estimated at 858.968,82 tons/year (Reduced by the amount of residual municipal waste 14.921,68 tons/year) .
It should be emphasized that each public utility company (PUC) collects waste and dispose of waste in the area for which it is responsible. Thus, the total potential of municipal waste to produce RDF should be taken with reserve, since the available quantities of municipal waste depend on the readiness and ability of the competent PUC to enter for the transfer of municipal waste to a third party.

Potential of packaging waste for RDF production
Next diagram sows the total quantities of packaging placed on the marked from 2010-2020.

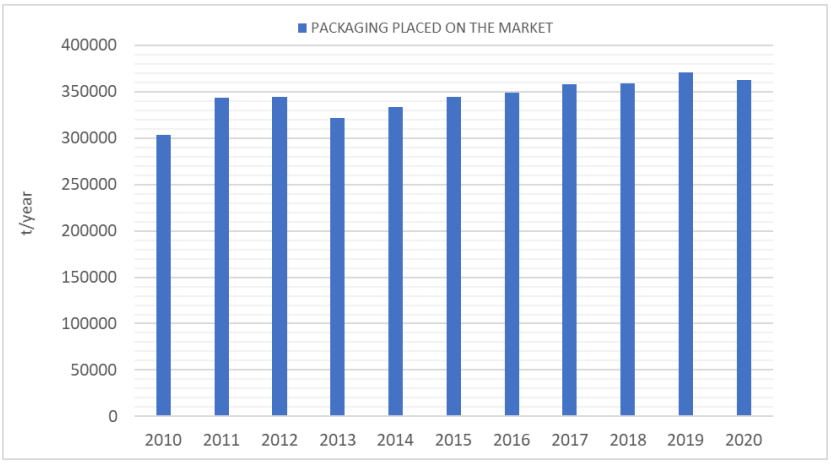


Fig. 1. *Quantity of packaging placed on the market of the Republic of Serbia by years [7]*

It can be assumed that all packaging placed on the market each year becomes waste in the same year. In the period from 2010 to 2020, the average amount of packaging waste is approximately 344.000 tons per year. The structure of the packaging material is expected to remain on average 20% glass, 27% plastic, 31% paper and cardboard, 4% metal, 18% wood and 1% other. Packaging waste potential for RDF production assessment included only paper/cardboard, plastic, and wood. In practice all packaging waste is not collected and recycled. Collected waste within EPR system, went to recycling and reuse process. In Figure 2 is a trend in the amount of packaging placed on the market and reused packaging waste in the period 2010 – 2020.

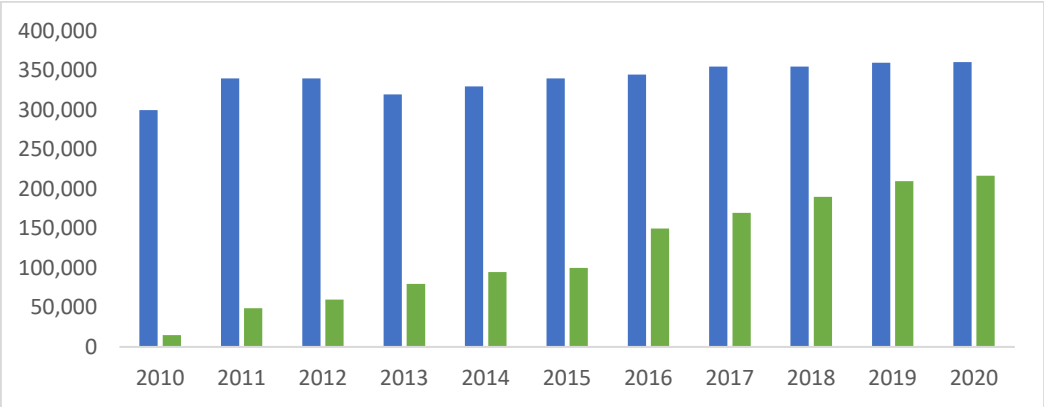


Fig. 2. *The amount of packaging placed on the market (blue bar) and reused packaging waste (green bar) in the period 2010 – 2020 [7]*

Based on latest report on management package and packaging waste for 2020, Serbia fulfilled the national targets for recycling and recovering of packaging waste whereas trough EPR system is collected and treated 186.833 tons/year of packaging waste fractions with potential for RDF production (plastic, paper and cardboard and wood). Therefore, analysis of potential for RDF production from packaging waste is based on residuals (25% residual waste) from treated collected packaging waste (EPR system).
Remaining uncollected packaging waste is landfilled and already included in municipal potential for RDF production. Packaging waste (PW) is generated in communal and non – communal sector (in industry and commercial sector).
Packaging waste from communal sector is collected by PUC in the municipality and it is already included in RDF potential from municipal waste in previous section, while from industry and commercial sector it is collected from PUC or through the EPR scheme. The sources of collected packaging waste within the EPR system are presented in figure 4.

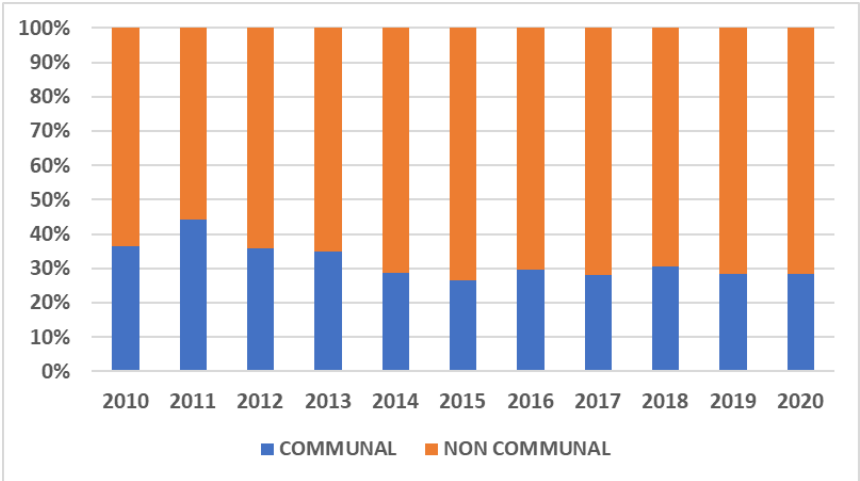


Fig. 4. *The sources of collected packaging waste within the EPR % (extended producer responsibility) system [8]*

The average share of communal packaging waste in the period between 2010 and 2020 is about 32%, while the share of non-communal packaging waste is about 68% on average.
The following table shows the total potential for RDF production from the residual waste after treatment (25% residual waste) in the Republic of Serbia. Total potential for production of RDF from residual communal and non - communal packaging waste (EPR system) is approximately 46.685,5 tons/year. The quantities of secondary wastes, which are generated during waste treatment operations, depend strongly on the level of the waste treatment infrastructure. Secondary waste fractions, that will be generated in the future (if the proposed infrastructure will be realized) could among others include output fractions of the biological part of RDF production plant (up to 60.000 t/year), organic residues and sludges from physical-chemical treatment (up to 12.000 t/year), and digestate form anaerobic digestion. The economic integration and rapprochement of Serbia with the European Union is likely to in-crease the exports as well as the imports of recyclable wastes like metal wastes, paper waste and plastic waste.

Potential of waste tires for production of RDF

Waste tires are defined as a non-hazardous waste (waste code 16 01 03) and therefor permits for collection, transport, treatment, storing, recovery and disposal, export and import are issued by the Ministry and authorities of Autonomous Provinces, Municipalities or Cities.
Article 49 of the LWM stipulates: "The entity that collects, transports, treats or disposes of waste tires shall hold appropriate permit, maintain, and keep records on quantities of collected and treated waste tires and shall submit such data to the Agency. The Minister shall closely prescribe manner and procedure for waste tires management."
Tires are covered by the Regulation on products that after use become special waste streams upon us thereof ("Official Gazette of RS", No. 54/10). Therefore, production or importation of tires has to be recorded and reported to SEPA on a yearly basis. This report is basis for taxation of a specific fee in line with the principle of extended producer responsibility.
Waste tires are defined as motor vehicle tires (cars, buses, trucks, motorbikes etc.), agricultural and construction machines, trailers, towed machines and so on, after the end of their life cycle, i.e. which owner rejects due to damage, wear and tear or due to other reasons. Tires for passenger cars and trucks represent about 85 % of the total number of produced tires.
The treatment options of waste tires include recycling of waste tires and use for energy purposes. At least 80 % of the waste tires should be recycled and not more than 20 % should be used for energy purposes because of the total quantity of waste tires collected in the previous year.
In accordance with Article 9 of the Regulation on disposal of waste in landfills ("Official Gazette of the Republic of Serbia ", No. 92/10) the landfilling of waste tires is prohibited.
There is a substantial production of car tires in Serbia with a high share of export. According to SEPA (2020) 39882.3 tons (e.g. tires from tractors, trucks, buses and fork lifters) of tires were put on the market in Serbia in2020. This quantity includes the tires produced in Serbia and the tires imported to Serbia in 2020.

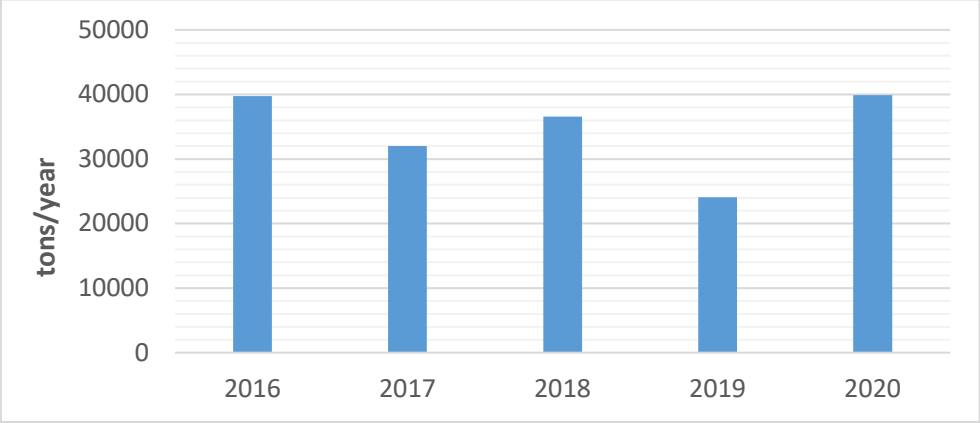


Fig. 5. *Quantity of tires put on the market 2016 – 2020 [9]*

If 80% of waste tires are recycled, ie about 31.905,84 tons in 2020, in that case about 7.976,46 tons/year can be used to produce RDF. Also, in 2020, about 177 tons of waste tires per year are landfilled, but it can be used for RDF production.
Waste tires are currently used as RDF in cement industry in Serbia. The amount incinerated (R1) in two cement plants was about 13.426 tons. About 27,000 t of waste tires were treated in recycling operations (R5). The installation of civic amenity sites is one tool to reduce the number of tires disposed of illegally. The generation of waste tires closely reflects the development of the car fleet. Based on the waste generation in 2016 in relation to the number of cars in use in Serbia and the predicted development of the car fleet (approx. 1,4% increase per year) a rise of waste generation from 42.175 tons in 2016 to 48.500 tons can be expected in 2024. The quantities of waste tires include also waste from stockpiles, the development of which is hard to predict. The following table summarizes the total potential for RDF production at the state and regional level.

Table 5. *The total potential for RDF production from selected waste streams at the state and regional level.*

Source	%	tons/year
Municipal solid waste*	94%	858.968,82*
Packaging waste (EPR system)	5.03%	46.686,5
Tires	0.88%	8.153,46
Total	100%	913.808,78

The total potential for RDF production at the state level is about 913.808,78 tons/year, of which approximately 5% refers to packaging waste collected through the EPR system, and rest and the rest represents RDF from residual municipal solid waste collected from PUC. A relatively small amount is represented by waste tires approximately 0.88%, or 8.153,46 tons/year.

CONCLUSION

The assessment of waste streams in Serbia indicates a substantial theoretical potential to produce refuse-derived fuel (RDF) at the national level. Based on current and projected municipal solid waste generation, the total potential for RDF production is estimated at approximately 914,000 tons per year. The largest share derives from residual municipal waste collected by public utility companies, while packaging waste from the Extended Producer Responsibility (EPR) system and waste tires contribute a smaller but still meaningful portion. These figures highlight that a significant fraction of non-recyclable waste could be diverted from landfills and instead utilized as an alternative energy source, supporting both national energy recovery strategies and broader environmental objectives.
However, realizing this potential depends heavily on the development of appropriate waste collection, pre-treatment, and processing infrastructure, as well as effective coordination with public utility companies and compliance with legislative requirements.
The successful integration of RDF production into Serbia's waste management and industrial energy systems could contribute to reducing landfill dependency, decreasing fossil fuel consumption, and promoting circular economy practices. At the same time, careful planning is needed to ensure that RDF utilization does not compete with existing recycling streams, and that environmental and social impacts are properly managed.

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REFERENCES

[1] EU for Environment. "Promoting Waste Source Separation in 4 Regions – Serbia." 2020. Available at: https://www.euzatebe.rs/en/projects/eu-for-environment--promoting-waste-source-separation-in-4-regions?utm_source=chatgpt.com
[2] Psomopoulos, C.S., Kiskira, K., Kalkanis, K., Leligou, H.C., Themelis, N.J. (2022) The role of energy recovery from wastes in the decarbonization efforts of the EU power sector. IET Renew. Power Gener. 16, 48–64 https://doi.org/10.1049/rpg2.12315
[3] Scarlat, N., Fahl, F. & Dallemand, JF. Status and Opportunities for Energy Recovery from Municipal Solid Waste in Europe. Waste Biomass Valor 10, 2425–2444 (2019). https://doi.org/10.1007/s12649-018-0297-7
[4] Kumar, A., Singh, E., Mishra, R., Lo, S.L., Kumar, S. (2023) Global trends in municipal solid waste treatment technologies through the lens of sustainable energy development opportunity, Energy, Volume 275,127471, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2023.127471.
[5] Ministry of Environmental Protection, Republic of Serbia. (2022) Waste Management Program in the Republic of Serbia for the period 2022–2031, Official Gazette of the Republic of Serbia, No. 12/22. Adopted by the Government of the Republic of Serbia on 28 January 2022. Available at: https://otpad.unecopn.org/upravljanje-otpadom-u-republici-srbiji
[6] Morfopoulos, N., Samolada, M.C.(2025) Effect of Waste-Derived Fuels (SRF/RDF) Composition on the Cement Industry's Environmental Footprint. Waste Biomass Valor https://doi.org/10.1007/s12649-025-03077-7
[7] Ministry of Environmental Protectionan of Republic of Serbia, SEPA - Serbian Evironmental Protection Agency, Report on Packaging and Packaging Waste Management in the Republic of Serbia in 2020. www.sepa.gov.rs.
[8] SEPA - Serbian Evironmental Protection Agency, Reports on Packaging and Packaging Waste Management 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020.
[9] SEPA, Products that after use become special waste flows in the Republic of Serbia, 2016-2020

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PRACTICES AND PERSPECTIVES OF SUSTAINABLE MANAGEMENT OF ORGANIC KITCHEN WASTE

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Abstract: Food waste poses significant economic, environmental, and social challenges, with households representing a major source of avoidable waste. This study presents preliminary results on the management of organic kitchen waste among residents of Zrenjanin and Novi Sad, Serbia, while also including participants from other regions of the country. The research aimed to assess participants' knowledge, attitudes, and practices regarding composting and household organic waste management. An online survey was conducted with 100 participants, collecting demographic information, knowledge about composting, and habits related to organic waste disposal. Results indicate that most participants are aware of composting and willing to adopt it; however, barriers such as limited space, high composter costs, and insufficient access to composting facilities remain significant, especially in urban areas.
Key words: Food waste, Organic kitchen waste, Household waste management, Composting

INTRODUCTION

Food waste carries significant economic, environmental, and social costs, making it essential to identify effective strategies for its reduction, particularly at the household level. Growing attention has been directed toward this issue, with a primary focus on edible food that could have been consumed but instead ends up discarded, as opposed to unavoidable waste such as vegetable peels or bones. Despite the rising interest, there remains a limited understanding of the factors that shape food-wasting behaviors, the development of effective policies and programs to mitigate such waste, and the appropriate methods for evaluating their impact [1]. Food waste refers to food that is discarded, spoiled or has deteriorated in the final stages of the supply chain, including distribution, retail and consumption. Each year about 1.6 billion tons of food, roughly one third of total global production, is thrown away worldwide and this amount is expected to rise to 2.1 billion tons by 2030. At the same time between 691 million and 783 million people around the world suffer from hunger and malnutrition due to lack of food [2]. A significant share of food waste is considered unavoidable, including peels, bones, fats, oils, and fresh food that has been mistakenly left to spoil. Separate collection of food waste improves treatment efficiency and also encourages waste reduction [3].
This paper presents the preliminary results of a study focusing on residents of Zrenjanin and Novi Sad, cities in the Republic of Serbia, while also including participants from across the country. The study examines how these residents manage organic kitchen waste, as well as their knowledge and attitudes regarding this issue.

MATERIAL AND METHODS

Challenges of Household Organic Waste Management

Improper management of food waste poses a serious risk to human health and the environment. Those most at risk include people living near poorly managed landfills, children, waste sector workers, and individuals consuming contaminated water. Food waste contributes to the development of infections, respiratory problems, and other illnesses, while its fermentation process releases methane and other harmful gases that affect climate change and air quality. Beyond health risks, food waste negatively impacts air, water, and soil, increases greenhouse gas emissions, and contributes to the depletion of natural resources. Landfills are major sources of pollution and inefficient resource use, and improper disposal of

waste can severely threaten ecosystems, particularly marine and coastal environments [4]. In households alone, each person, on average, throws away significantly more than the average adult body weight every year, and food waste from retail, hospitality, and households combined weighs more than twice the average human body weight. In 2022, it is estimated that the world discarded around 1.05 billion tons of food across the retail, hospitality, and household sectors. This amounts to 132 kilograms of food per person per year, of which 79 kilograms per person were thrown away in households [5]. The food waste management hierarchy emphasizes preventing waste as the most important step, through better planning of production and distribution, saving resources like energy, water, nutrients, and labor. Food that is still safe but cannot be sold should be redistributed to those in need, while inedible parts can be used as animal feed according to regulations. Recycling methods include anaerobic digestion, producing biogas and fertilizer, and composting, which enriches soil. Incineration with energy recovery recovers some energy but is less efficient. The least desirable options are landfilling, incineration without energy recovery, and disposal into sewage, all causing resource loss and environmental harm. Effective management requires measuring and classifying waste to identify sources and apply targeted measures [3].

Strategies for Reducing Household Food Waste

There are various factors that motivate households to reduce food waste. Among the most important are saving resources, particularly money and time. Saving money has been shown to be one of the strongest motivators for reducing food waste. Additionally, reducing waste has broader social and ethical benefits, as it helps increase the value we place on farmers and raises awareness of food scarcity issues. For example, meal planning, checking food supplies before shopping, and using shopping lists can reduce the amount of food discarded. Planning portion sizes and considering food packaging can also help minimize waste by avoiding the purchase of excess quantities. A key element of successful food management is a high level of consumer self-control [6].

Compost is an effective alternative fertilizer that significantly impacts soil organic matter and microorganisms. Maintaining microbial diversity in the soil is crucial for nutrient cycling and other biological processes. Compost also enhances microbial activity and biomass, leading to better plant growth and overall yield. Compost increases the number of beneficial microorganisms, including bacteria and fungi, which improve nutrient availability and break down harmful substances. The composition of compost affects microbial activity and CO_2 emissions in the soil. Additional benefits include reducing unpleasant odors and eliminating pests such as insects and rodents [7]. Composting of organic waste involves changes that result in the mineralization and mobilization of nutrients such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na). Nitrogen is transformed through the processes of ammonification, nitrification, and denitrification, while phosphorus changes its availability during the process. Potassium is stable and remains in the compost in the form of soluble salts. Other elements, such as calcium and magnesium, increase due to mineralization. The composting process also produces humic substances, which are essential for compost maturation and its use in agriculture [8].

RESULTS AND DISCUSSION

The study was conducted through an online survey, which was divided into three sections:

1. **Basic information about the participant**: collecting demographic data such as age, gender, place of residence, and similar details.
2. **Participant knowledge**: a section focused on assessing participants' knowledge about composting and proper disposal of kitchen organic waste.
3. **Attitudes and behaviors**: a section addressing participants' attitudes toward managing kitchen organic waste and their everyday practices related to it.

The sample size was limited as these results are **preliminary**. The study included 100 participants, of whom 52 were from the city of Zrenjanin, 15 from Novi Sad, and 33 from other regions of Serbia. The survey was distributed through social media channels. Regarding **place of residence**, 75 participants live in the city, 16 in rural areas, and 9 in suburban settlements. The majority of participants were female, with 74 women and 26 men taking part in the study. The study included participants from all **age groups**, ranging from 18 to over 65 years. The largest number of participants, 40, belonged to the 25-34 age group, followed by 21 participants in the 45-54 age group. A slightly smaller number, 14, were aged 35-44, 12 participants were in the 55-64 age group, and one participant was over 65 years old.
Participants **knowledge** of the **composting process** can be considered positive. When asked if they knew what composting is, 54 participants answered that they knew exactly, 28 said they had a general idea, 11 had heard the term but did not know its meaning, and 7 had never heard of it. After being shown the definition of composting, 98 participants stated that it was now completely clear to them what composting is, while 2 participants said it was partially clear. Figure 1 shows the participants knowledge: part A, before the provided definition of composting, and part B, after reading the definition of composting.

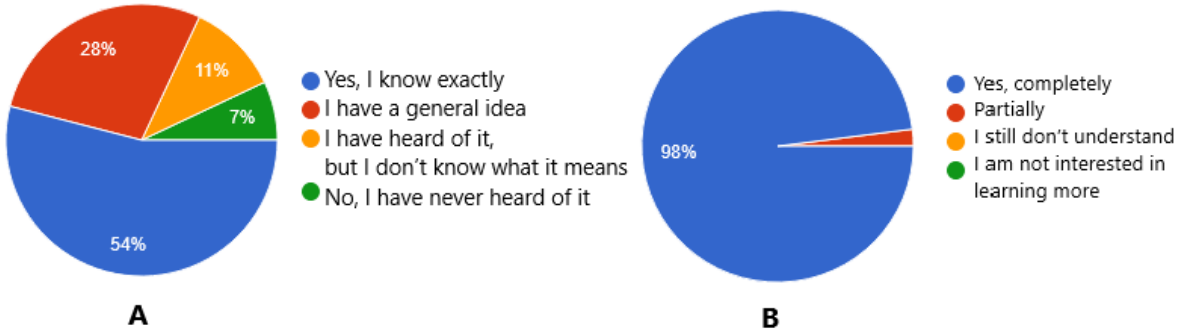


Fig. 1. *Participants' knowledge of composting: (A) before the provided definition, (B) after reading the definition*

Regarding their habits and behaviors, 41 participants reported that they do not separate organic kitchen waste at home, 31 participants sometimes separate it, and 28 participants always separate kitchen waste. These results are shown in Figure 2.

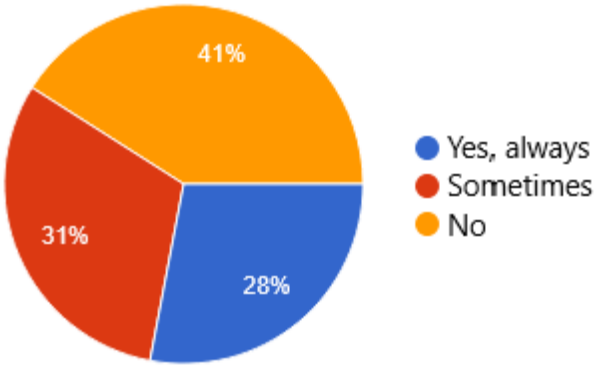


Fig. 2. *Participants' practices in separating organic kitchen waste at home*

Concerning the possibility of composting, 53 participants stated that they do not have the opportunity to compost organic kitchen waste in their place of residence, 35 participants reported having this opportunity, and 12 participants were not aware whether such a possibility exists in their area. The responses to this question are presented in Figure 3.

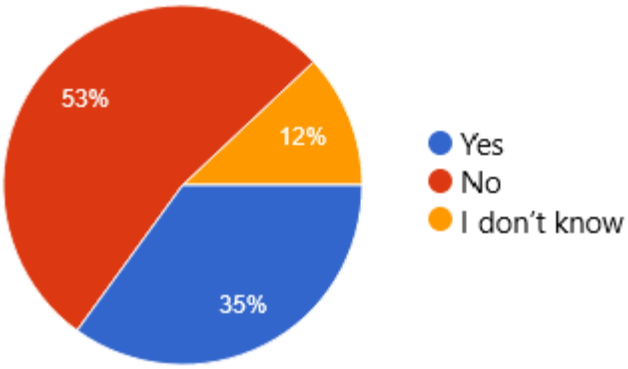


Fig. 3. *Participants' access to composting opportunities in their place of residence*

If offered the opportunity, 72 participants stated that they would definitely use a composter in their household, 25 said they might consider using one, while 3 indicated that they would not use it. This suggests a strong willingness among the majority to adopt composting practices at home.

The Main Challenges in Managing Kitchen Waste

This section presents the most significant responses (R) from participants regarding the biggest challenges they face in managing kitchen organic waste. Special attention is given to the issues most commonly encountered in households, including obstacles related to disposal, composting, and everyday waste management practices.

R1.

„For my family: the high cost of a composter and the inability to make one at home. For most people: insufficient education and lack of access to composting opportunities."

R2.

„There are no major challenges except for building a composter. The main challenge is for people living in apartments without a yard, due to living conditions and lack of space, which makes it difficult, for example, to use a Bokashi bin or similar systems."

R3.

„At home, I successfully separate organic waste, but the biggest challenge is when I am not at home and cannot control how household members dispose of it."

R4.

„Providing space for composting, government subsidies and incentives, and raising awareness through various educational programs and seminars."

R5.

„Insufficient living space for composting and the effort required to properly dispose of the compost."

R6.

„In the city, there are generally no conditions for proper disposal of organic waste, and consequently, there is little awareness about the need for sorting it. In rural areas,

specifically in my family, all organic material is fed to animals, such as vegetable scraps, or added to compost. However, there are also cases I have seen where people in villages put all their organic waste into plastic bags, which would end up in illegal dumps."

Based on the participants responses, it can be concluded that the main challenges in managing kitchen organic waste are linked to a combination **of lack of resources, space, knowledge, and awareness.** The high cost of a composter and the inability to make one at home are significant obstacles, particularly in urban areas, while people living in apartments without a yard face additional difficulties due to limited space and unsuitable conditions for using systems like a Bokashi bin. Although many participants successfully separate organic waste at home, challenges arise when they are not present and cannot control how other household members dispose of it. Furthermore, there is a clear need for providing space for composting, government subsidies and incentives, and raising awareness through educational programs and seminars. Differences between urban and rural areas are also evident, in cities, proper disposal conditions and awareness of waste sorting are often lacking, whereas in rural areas, organic waste is mostly used for feeding animals or composting, although there are cases where it is placed in plastic bags and ends up in uncontrolled or illegal disposal sites.

CONCLUSION

The preliminary results of this study indicate that household management of organic kitchen waste in Serbia is influenced by a combination of factors, including knowledge, available space, resources, and individual habits. While a majority of participants are aware of composting and demonstrate positive attitudes toward separating organic waste at home, practical challenges such as high composter costs, limited living space, particularly in apartments without yards, and lack of access to composting facilities hinder consistent waste management. Participants also highlighted the importance of educational initiatives, government incentives, and the provision of proper infrastructure to support composting practices. Differences between urban and rural areas are evident: in rural households, organic waste is often utilized for animal feed or composted, whereas in urban settings, the lack of proper disposal conditions and awareness contributes to inefficient waste management. Overall, the study underscores the need for targeted interventions combining awareness-raising, policy support, and practical solutions to facilitate effective household food waste management and promote sustainable composting practices. As a preliminary study with a limited sample, these results should be considered indicative, and further, more representative research is needed to confirm these trends.

REFERENCES

[1] P. van der Werf , . J. A. Seabrook i J. A. Gilliland, „"Reduce Food Waste, Save Money": Testing a Novel Intervention to Reduce Household Food Waste," Environment and Behavior, 2021.
[2] S. Zahra, A. Anggrainy, Z. Mohd-Zaki i A. Bagastyo, „Food waste reduction strategies in composting and recycling centers based on material flow analysis," Global Journal of Environmental Science and Management,167-180, 2024.
[3] S. Jain, D. Newman, R. Cepeda-Márquez i K. Zeller, „Global Food Waste Management: an implementation guide for cities," 2018.

[4] E.-D. Ungureanu-Comanita, E. L. Cosbuc, P. Cozma, C. Smaranda i M. Gavrilescu, „Human Health Risks Concerning Food Waste," u The 8 th IEEE International Conference on E-Health and Bioengineering - EHB 2020, Iasi, Romania, 2020.
[5] UNEP, „Food Waste Index Report 2024. Think Eat Save: Tracking Progress to Halve Global Food Waste," 2024.
[6] T. Begho i O. Fadare, „Does household food waste prevention and reduction depend on bundled motivation and food management practices?," Cleaner and Responsible Consumption, 2023.
[7] T. Sayara, R. Basheer-Salimia , F. Hawamde i A. Sánchez, „Recycling of Organic Wastes through Composting: Process Performance and Compost Application in Agriculture," Agronomy, 2020.
[8] E. E. Manea, C. Bumbac, L. R. Dinu, M. Bumbac i C. M. Nicolescu, „Composting as a Sustainable Solution for Organic Solid Waste Management: Current Practices and Potential Improvements," Sustainability, 2024.

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THE MICROBIOLOGICAL CONTROL OF DEMINERALIZED WATER

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Abstract: Demineralized water is the basic raw material for the production of cosmetic products and household chemistry products at Beohemija DOO. Demineralized water is produced by reverse osmosis and every part of the process is subject to microbiological control, due to monitoring the state of the equipment itself from a microbiological aspect as well as obtaining the correct final product.
Key words: reverse osmosis, demineralized water, microbiological control

INTRODUCTION

In the field of water treatment and purification, the process of obtaining demineralized water by reverse osmosis (RO) represents an exceptional technological achievement. Reverse osmosis is very effective at removing a wide range of impurities, including most minerals and ionized substances [1,2] Unlike ion exchange columns that use a strong acid or base for regeneration, reverse osmosis is much "greener" and cheaper to operate [2,3,4]. Demineralized water is often used in the production of various types of household chemicals, including detergents, cleaners, disinfectants, and many other products. This type of water is also useful in the cosmetics and pharmaceutical industries, where its high purity and stability are also appreciated.
The aim of this work is the microbiological control of demineralized water produced by reverse osmosis in Beohemija DOO, which is the basic raw material for the production of cosmetic products and household chemistry products.

The process of demineralized water production in Beohemija DOO

The demineralized water production process at Beohemija DOO aims to produce demineralized water of appropriate quality: hardness, conductivity and pH value.
Demineralized water is used as a basic raw material in the household chemicals production plant in Beohemija DOO, as well as in the production of technological steam in thermal power plants.
Water softening is the process of replacing calcium and magnesium ions from water hardness salts with sodium ions, and is carried out in ion exchangers. Ion exchangers are devices filled with special ion exchange masses that exchange ions. Calcium and magnesium ions from water bind to the ion exchange mass, and an equivalent amount of sodium ions is released from the mass. Of course, this replacement cannot last indefinitely and is limited by the amount of sodium ions in the ion exchange mass of the ion exchanger, which means that calcium and magnesium salts are converted into an equivalent amount of sodium salts by softening [1,8]. The resulting sodium salts are extremely soluble in water and do not form scale. Sodium bicarbonate resulting from carbonate hardness is known as baking soda.

Devices used in water softening

1.) The specialized container intended for the preparation of the scavenger regeneration solution is shown in Fig. 1. The solution preparation process begins with the use of water from the scavenger, to which 100 kg of tableted salt is added. During every third regeneration, 10 kg of previously dissolved sodium hydroxide (NaOH) in 30 kg of

demineralized water is added to the solutionthe (vessel should be filled in a ratio of 1/3 salt and 2/3 water).



Fig. 1. *Preparation of regeneration agent for scavenger*

2.) The pre-sand filter has the role of keeping any dissolved substances from the raw water (organic substances) on it. The role is played by a 25 μm filter cloth. The replacement of the filter cloth is done when the pressure of the feed water, that is, as soon as there is a difference in the pressure at the inlet compared to the outlet (of 1 bar).

3.) The sand filter is filled with different sand fractions whose role is to remove mechanical impurities from the water. Over time, the filter filling (sand) of the sand filter becomes clogged (dirty) with impurities from the water, so it is necessary to wash the sand filter. Filter washing is also done by a combination of co-current and counter-current washing with raw water. Rinsing must be done once a week, and if necessary, more often, when the production of demi water allows it. Rinsing is done first against the current, while it visually looks like the incoming water. The performed filter washing is recorded in the daily report of the plant for the production of demi water, steam and hot water. The length of sand filter flushing depends on both the amount of technical water that passed through it and its quality. Rinsing of the sand filter can also be done in situations where there is a difference in the pressure value at the exit and entry into the sand filter. After the sand filter, the purified water from mechanical impurities goes to the ion exchange column.



Fig. 2. *Pre-sand filter, sand filter and scavengers*

4.) The scavenger serves to soften water and contains ion exchange filters (softeners), which consist of an ion exchange column filled with a certain amount of ion exchange mass. Currently, resinexa TPS4500 type ion exchange resin is used. The resin removes dissolved organic matter from the feed water. When the mass is saturated, by passing the table salt solution and the NaOH solution, it is converted back into an active form and the resin is ready for softening a certain amount of water (Fig. 2). Regeneration of each scavenger is done once per shift with NaCl solution, and every third regeneration is done with NaCl and NaOH solutions.
In Beohemija DOO, for the production of liquid detergents, softened water is needed 24 hours a day, without interruption, so in that case automatic duplex softeners-scavengers are used. These are two devices connected in parallel, while one is working, the other is being regenerated, when the working device is saturated, the automation switches the already regenerated device into the working phase, with this distribution it is achieved that one device is always ready for work. All stages of regeneration can be time-adjusted and adapted to a certain capacity of the device.
In the working phase, water flows through the control valve, flows around the central pipe, passes through the ion exchange mass and enters the central pipe through the lower nozzle, from where it is drained to the place of consumption. The working capacity of the softener is about 100 m³ of water, which depends on the amount of ion exchange mass and the hardness of the feed water. After the capacity is exhausted, the softener regenerates and becomes ready for water treatment again.
It is important to note that about 10% of the produced demineralized water is used for the regeneration process. Before reverse osmosis, antiscalant is automatically added to the softened water, and analysis of the softened water is performed once per shift, including the measurement of conductivity (1100-1250 μS/cm) and pH value (7.4-7.9). $KMnO_4$ consumption is monitored daily, mostly in the first shift. Also, a chlorine remover is added before reverse osmosis. All results are recorded in the daily report of the plant for the production of demi water, steam and hot water. This complex process ensures continuous availability of high-quality demineralized water, which is crucial for efficient production and plant maintenance (Fig. 3). Scavenger regeneration is programmed to last 144 minutes.

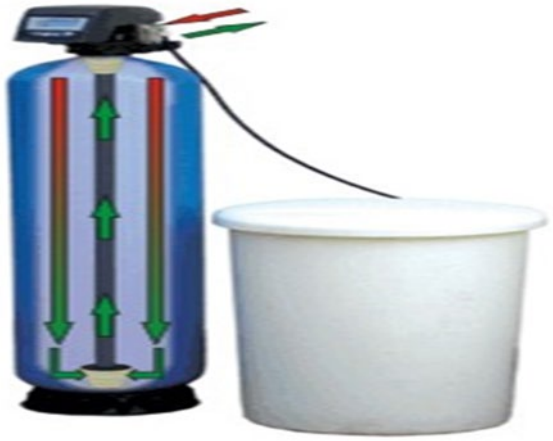


Fig. 3. *Scavenger work phase*

The phase of countercurrent washing of the ion exchange mass is a key step in the process of regeneration of ion exchange columns. During this stage, the water is diverted through the central pipe to the bottom of the column, from where it passes through the ion exchange mass upwards and finally drains into the sewer from the top of the column. The goal of this phase is multiple. First, it enables efficient washing of mechanical impurities that have arrived with the feed water (Fig. 4.).



Fig. 4. *Countercurrent rinsing phase*

Reagent entrainment phase is shown in Fig. 5. In this phase, a solution of sodium chloride (table salt) and NaOH is passed through the device, whereby the ion exchange mass is regenerated and converted back into an active form. The salt solution is drawn in from the salt container via an injector built into the control valve. For one regeneration, 100 kg of tableted salt is consumed, and for every third regeneration, 10 kg of NaOH is added.



Fig. 5. Reagent loading phase

The slow wash phase is a continuation of the reagent draw phase. In this phase, water is drawn in directly from the sand filter (Fig. 6.)



Fig. 6. Slow rinse phase

During the fast flushing phase, the flow of water through the device is the same as during the working phase, with the fact that the output water is not directed to the output connection, but to the sewage system. Which column is in operation and which is being regenerated, the regeneration time, as well as the amount of NaOH consumption, are entered by the operators in the daily report. At the end of the regeneration process, a certain amount of water is returned to the brine (approximately 500 l), to which salt and, if necessary, sodium hydroxide are added later, and the solution is ready for the next regeneration.

5.) Reverse osmosis system, shown in Fig. 7. Water flows over the surface of the membrane under high pressure, water molecules pass through the membrane and are collected in the permeate collector that separates it [5,6]. Molecules of dissolved salts are concentrated in the part of the water that flows over the surface of the membrane and that part is taken out of the module as a concentrate, which is rejected 5-6 m³/h) and the flow of the concentrate 5m³/h which is entered in the days report once in a shift. Demineralized water automatically goes into receiving vessels, each of 25 m³. Analysis of demineralized water is performed once per shift and entered in the daily report. When the permeate flow drops below 5m³/h, it is necessary to rinse the membranes according to the instructions[7].
The basic element of the reverse osmosis device is the so-called RO module. The RO module consists of a reverse osmosis membrane (RO membrane) placed in its housing. Currently, membranes manufactured by TORAY type TMG20-400C are in use. The membrane is made of special materials through which small molecules can pass, while the passage of larger molecules is impossible.
6.) Demineralized water automatically goes into receiving vessels 7a and 7b, each with a volume of 25 m³ (Fig. 8).



Fig. 7. *Reverse osmosis system*



Fig. 8. *Acceptance court for demineralized water*

MATERIAL AND METHODS

The material was demineralized water from parts of the plant: scavenger and reverse osmosis and from receiving vessels. Control of the microbiological correctness of demineralized water was carried out in the microbiological laboratory of Beohemija DOO in Zrenjanin, according to the Rulebook on methods for determining the pH value and the amount of toxic metals and non-metals in personal hygiene products, care and beautification of the face and body and for determining the microbiological correctness of these products (Official Gazette of the SFRJ No. 46/83) [9]. The procedure for taking samples of demineralized water was carried out in accordance with the Rulebook on the method of taking samples and methods for laboratory analysis of drinking water (Official Gazette of the SFRJ No. 33/87) [10].

RESULTS AND DISCUSSION

The results of microbiological analysis of demineralized water from both scavengers, reverse osmosis systems, under UV lamps and receiving vessels are shown in Table1.

Table 1. *The results of microbiological analysis of demineralized water*

Designation of the sample	Total number of aerobic mesophilic microorganisms Max 1000/g/ml	*Escherichia coli* negative in 1g/ml	*Pseudomonas aeruginosa* negative in 1g/ml
RS-9A	0	0	0
RS-5B	0	0	0
Under a UV lamp	0	0	0
After Reverse Osmosis	0	0	0
Scavengers	>100	0	0
RS-9A	0	0	0
Under a UV lamp	0	0	0
After Reverse Osmosis	0	0	0
RS-9A	0	0	0
RS-7A	0	0	0
RS-5B	0	0	0
Under a UV lamp	0	0	0
RS-7A	0	0	0
RS-7B	0	0	0
Under a UV lamp	0	0	0

Microbiological analysis of demineralized water in the Scavenger water purification system, on Nutrient Agar after 24 hours of incubation, showed the growth of colonies of microorganisms, but within the permitted limits (Fig. 9). Growth of *E. Coli* was not present as determined by the presence of gas in Durchmann's tubes in brilliant green lactose bile broth after 24h, growth of *P. aeruginosa* was also not detected.

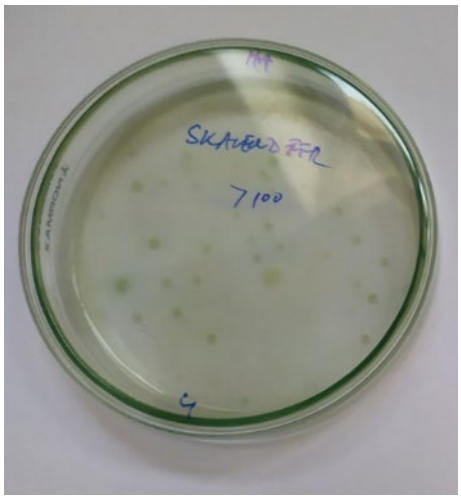


Fig. 9. *Total number of aerobic mesophilic microorganisms on Nutrient Agar after 24h*

In the microbiological analysis of demineralized water, leachate from the column, receiving tank RS - 5B, for receiving tank RS - 9A and after reverse osmosis, the total number of aerobic mesophilic microorganisms on Nutrient Agar after 24 hours of incubation showed no growth (Fig. 10).

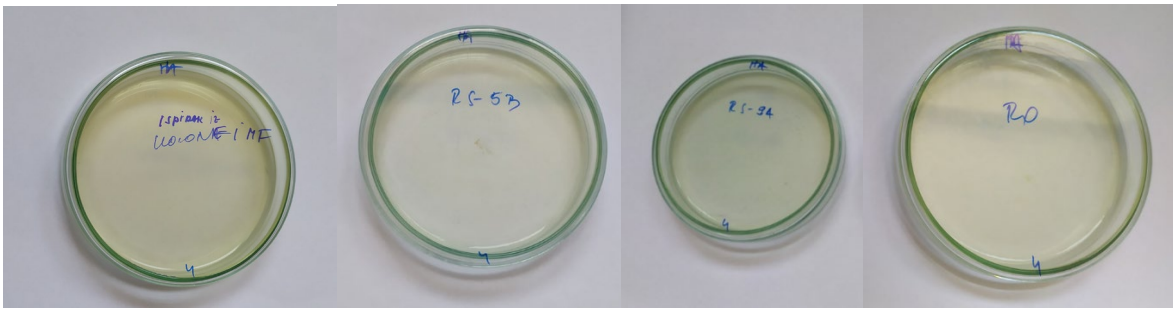


Fig. 10. *Total number of aerobic mesophilic microorganisms on Nutrient Agar after 24h*

CONCLUSION

Demineralized water is the basic raw material for the production of household chemicals and as such occupies an important place in the production process itself, therefore it is clear that its microbiological quality is of crucial importance.
Microbiological analysis of the basic raw material of demineralized water obtained by the reverse osmosis method in Beohemija DOO, showed that it meets the requirements given in the valid legal regulations of the Republic of Serbia.

REFERENCES

[1] Čuda P., Pospíšil P., Tenglerová J., Reverse osmosis in water treatment for boilers. Desalination, v. 198, pp. 41–46, 2006.
[2] Oosterom H. A., Koenhen D. M., Bos, M., Production of demineralized water out of rainwater: environmentally saving, energy efficient and cost effective., Desalination, v. 131, pp. 345-352, 2000.
[3] Braun G., Hater W., Kolk C. Z., Dupoiron C., Harrer T., Gotz T., Investigations of silica scaling on reverse osmosis membranes. Desalination, v. 250, pp. 982-984,2010.

[4] González A. P., Urtiaga, A. M., Ibánez R., Ortiz I., State of the art and review on the treatment Technologies of water reverse osmosis concentrates., Water Research, v. 46, pp. 267-283, 2012.
[5] Zanin Rovani M., Kamradt Savi L., Igarashi Mafra L., Mottin Demiate I., Study of production of reverse osmosis demineralized water for boilers., B.CEPPA, Curitiba, v. 35, 2017.
[6] Lee J.W., Kwon T.O., Moon S., Performance of polyamide reverse osmosis membranes for steel wastewater reuse., Desalination, v. 177, pp. 69-82, 2009.
[7] Mohammadi T., Moghadam M. K., Madaeni S. S., Hydrodynamic factors effecting flux and fouling during reverse osmosis of seawater., Desalination, v. 151, pp. 239-245, 2002.
[8] Interna dokumentacija Beohemija DOO, Zrenjanin
[9] Pravilnik o metodama za određivanje pH vrednosti i količine toksičnih metala i nemetala u sredstvima za odžavanje lične higijene,negu i ulepšavanje lica i tela i za utvrđivanje mikrobiološke ispravnosti tih sredstava (Službeni list SFRJ br.46/83)
[10] Pravilnik o načinu uzimanja uzoraka i metodama za laboratorijsku analizu vode za piće (Službeni list SFRJ br. 33/87).

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UNSUPERVISED MACHINE LEARNING vs. CLASSICAL CLUSTERING: HOTSPOT IDENTIFICATION OF PBDEs IN DANUBE RIVER SEDIMENTS

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Abstract: This study investigates the concentrations of ten PBDE congeners in Danube River bottom sediments and identifies contamination hotspots using hierarchical cluster analysis (HCA) and k-means clustering. Σ10PBDE ranged from 0.52 to 31.21 µg/kg d.w., with BDE-209 dominating. HCA grouped sites according to congener profiles and overall burden, while k-means, based on a neural network learning principle, provided enhanced resolution of high-risk sites. Both approaches identified Neštin, D6 and D10 as hotspots. The combined application of classical and machine-learning clustering is recommended for improved prioritisation of monitoring and management efforts.
Key words: PBDEs, sediment, Danube, water pollution

INTRODUCTION

River sediments are key environmental compartments that act as both sinks and potential secondary sources of hydrophobic contaminants. Due to their fine-grained structure and high organic carbon content, sediments accumulate lipophilic pollutants such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and brominated flame retardants (BFRs) [1,2]. Once deposited, these substances can persist for years, undergoing remobilisation during hydrological events, dredging, or resuspension, thereby reintroducing contaminants into the water column and food web [3].
Polybrominated diphenyl ethers (PBDEs), widely used as flame retardants in plastics, textiles and electronics, are of particular concern because of their persistence, bioaccumulation potential, and toxicity. Laboratory and field studies have linked PBDE exposure to endocrine disruption, neurodevelopmental deficits, and carcinogenic effects [4,5]. In aquatic ecosystems, PBDEs can accumulate in sediments, where they pose risks to benthic organisms and enter the trophic chain via bioaccumulation and biomagnification [6]. The Danube River, as Europe's second largest river, flows through multiple countries and receives diverse anthropogenic inputs, making it a crucial hotspot for transboundary pollution studies.
The analysis of PBDEs in sediments is not only important for establishing contamination levels but also for identifying critical sites ("hotspots") that require focused monitoring and management. Statistical and machine-learning approaches have been increasingly employed to classify sediment quality data and detect hidden structures in complex datasets [7,8]. Hierarchical cluster analysis (HCA) has traditionally been used to group sampling sites based on similarity in contaminant profiles, whereas k-means clustering—rooted in artificial neural networks and unsupervised machine learning—offers a more advanced, iterative optimisation that can reveal subtle boundaries between clusters [9].
This study aims to (i) quantify PBDE concentrations in Serbian Danube sediments, (ii) apply both HCA and k-means to identify contamination hotspots, and (iii) compare the effectiveness of these two approaches. By integrating conventional multivariate statistics with neural

network-based clustering, the research demonstrates the value of combining classical and modern data analysis tools in environmental monitoring.

MATERIAL AND METHODS

Sediment sampling and analysis

Sediment samples (0–10 cm, <63 μm fraction) were collected from ten sites along the Serbian Danube (Fig.1). Composite samples were homogenised, freeze-dried and extracted (Soxhlet, toluene), with clean-up by silica/charcoal columns. PBDE congeners were quantified by GC-MS. Surrogate recoveries were 78–112%, blanks were below LOQ, and precision was within ±15%. Concentrations are reported on a dry-weight basis.

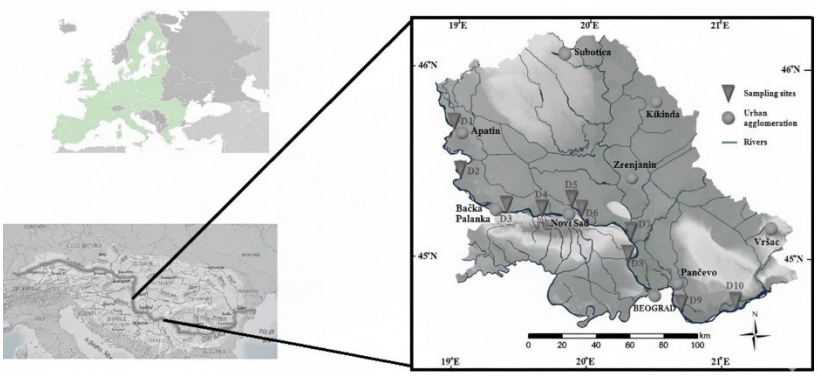


Fig. 1. *Map of the sampling sites*

Statistical analysis

Concentration data (Σ10PBDE and individual congeners) were standardised and processed using SPSS and MATLAB.
Hierarchical cluster analysis (HCA): Ward's linkage with squared Euclidean distances.
k-means clustering: iterative partitioning into 3–5 groups, optimised using silhouette scores. The method follows the learning principle of unsupervised artificial neural networks and represents a fundamental building block of deep learning algorithms [9,10].

RESULTS AND DISCUSSION

Concentration ranges and congener profiles

PBDEs were detected in all sediment samples, with Σ10PBDE concentrations spanning a broad range from 0.52 to 31.21 μg/kg d.w., and a mean value of 8.09 μg/kg. Such variability reflects both spatial heterogeneity in contaminant inputs and differences in sediment properties, including grain size and organic matter content. The congener profile was dominated by BDE-209 (Figure 2), which is consistent with the widespread historical use of technical deca-BDE formulations in plastics, textiles, and electronic housings. BDE-209 is highly hydrophobic and persistent, and its prevalence in sediments indicates both ongoing release from materials still in use and its long-term accumulation in depositional zones.
At several locations, additional congeners made notable contributions. BDE-47 and BDE-99, two of the major constituents of penta-BDE technical mixtures, were detected at elevated proportions in specific sites, suggesting localised inputs from urban or industrial discharges, as well as possible in-situ debromination of higher congeners. The occurrence of BDE-183, typically associated with octa-BDE mixtures, was particularly enriched at site D6, indicating potential inputs from polymer processing or waste-related sources, such as leachates from obsolete electronics and construction materials. In contrast, D10 exhibited a strong dominance

of BDE-209 with limited contributions from lower congeners, pointing to point-source contamination dominated by deca-BDE.
The highest Σ10PBDE concentration was observed in Neštin (D3), where both absolute levels and relative enrichment of mid-brominated congeners suggest upstream transport combined with local sedimentary retention. Taken together, these compositional patterns highlight that technical deca-BDE formulations were the primary sources of PBDEs in the investigated stretch of the Danube, while the detectable presence of tetra- to hepta-BDE congeners reflects secondary inputs from penta- and octa-mixtures, as well as environmental transformation processes such as photolytic or microbial debromination. These findings emphasise that sedimentary PBDE profiles can provide insights not only into contaminant levels but also into the relative importance of historical use, ongoing emissions, and degradation pathways.

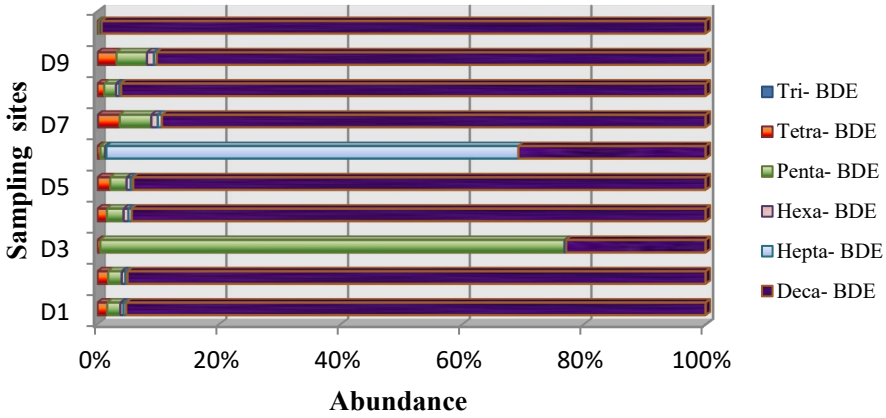


Fig. 2. *Distribution of PBDEs in the riverbed sediment from Danube River*

Hotspot identification by HCA

Hierarchical cluster analysis (HCA) grouped the sampling sites into three major clusters (Fig. 3), providing an intuitive overview of similarity patterns across the Danube sediment dataset. Cluster I comprised sites with low Σ10PBDE contamination, generally below 2 μg/kg, where congener profiles were dominated by trace levels of BDE-209 and negligible contributions of other congeners. These locations can be considered background or reference sites, reflecting either limited anthropogenic influence or depositional environments less prone to contaminant accumulation.
Cluster II included sites with moderate PBDE concentrations (2–10 μg/kg), in which BDE-209 was clearly the predominant congener. This cluster reflects areas where deca-BDE inputs are present but not extreme, likely corresponding to diffuse sources such as runoff from urbanised catchments, abrasion of treated materials, or gradual release from industrial and municipal waste streams. Importantly, the sites in this cluster displayed relatively homogeneous profiles, suggesting a common source signature dominated by technical deca-BDE.
Cluster III contained the identified hotspots: Neštin (D3), D6, and D10. These sites showed markedly higher Σ10PBDE levels, reaching up to 31.21 μg/kg, and exhibited distinct compositional patterns. Neštin (D3) was characterised by both elevated concentrations and the presence of mid-brominated congeners (BDE-47, -99), indicating upstream transport coupled with local depositional processes. Site D6 was enriched in BDE-183, pointing to contributions from octa-BDE mixtures or e-waste-related leachates, while D10 was dominated by BDE-209, consistent with a localised deca-BDE input.
The dendrogram provided a clear hierarchical framework to visualise these relationships, where the progressive branching illustrated how sites with similar contaminant signatures clustered together. This structure is particularly useful for identifying not only extreme hotspots but also intermediate contamination groups, enabling prioritisation of monitoring efforts. By revealing both shared patterns and site-specific anomalies, HCA offered a straightforward but

powerful tool for evaluating the spatial organisation of PBDE contamination in the Danube sediments.

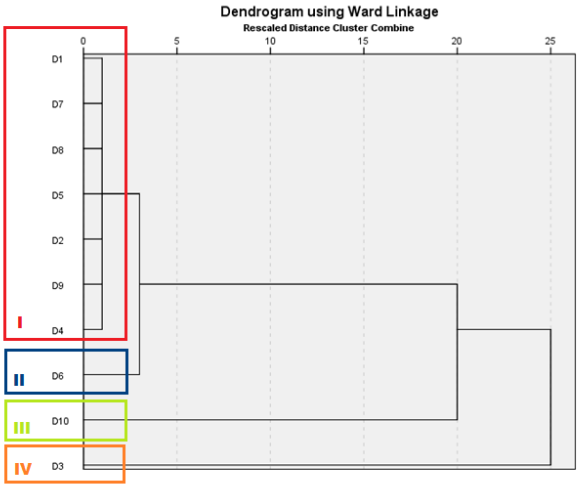


Fig.3. *Cluster dendograms of PBDEs identified in ten tested samples*

Hotspot identification by k-means clustering

The application of k-means clustering produced more nuanced and differentiated groupings compared to HCA, particularly when dealing with sites that exhibited similar Σ10PBDE concentrations but diverged in their congener composition. While HCA provided a broader overview of relationships, k-means, through its iterative partitioning algorithm, succeeded in capturing subtle differences among sites, reflecting its higher sensitivity to internal cluster variability.

Neštin (D3) consistently emerged as the centroid of a high-risk cluster, which confirmed its status as the most contaminated site within the studied river stretch. The elevated Σ10PBDE concentration, combined with the presence of both deca- and penta-BDE related congeners, positioned D3 as a focal point of concern. In contrast, D6 and D10 were identified as distinct outliers, each characterised by unique contaminant profiles. D6 showed a notable enrichment of BDE-183, suggesting inputs from octa-BDE formulations or leachates associated with e-waste disposal, whereas D10 was dominated almost exclusively by BDE-209, pointing to a strong, localised deca-BDE source.

This ability of k-means to highlight intra-cluster variability and distinguish between superficially similar sites illustrates the advantage of neural-network-based clustering over classical hierarchical approaches. Unlike HCA, k-means does not rely on a static tree-like structure but continuously updates group assignments until the optimal partitioning is achieved. This iterative optimisation, rooted in the principles of unsupervised machine learning, ensures that the method can adapt to complex and non-linear patterns in environmental datasets. Furthermore, k-means allows probabilistic interpretation of cluster membership, which is particularly relevant in transitional zones where sites may display characteristics of both moderately contaminated and hotspot groups. Such flexibility provides a richer and more realistic representation of sediment contamination dynamics.

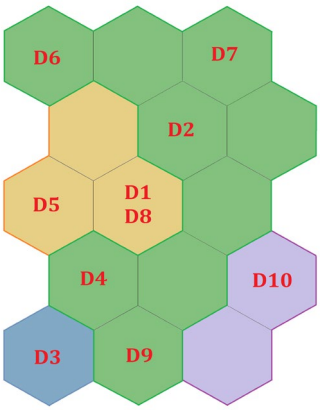


Fig.4. *k-means algorithm for PBDEs*

Comparison of methods

Both HCA and k-means clustering effectively identified contamination hotspots along the Danube River, yet their interpretive strengths and practical applications differ. HCA provided a straightforward, hierarchical visualisation of site similarities, enabling researchers to rapidly identify groups of sites that share common contamination signatures. Its dendrogram structure is simple to interpret and particularly useful in the initial exploratory phase of data analysis, where a broad overview of patterns is required. However, the rigid, stepwise nature of HCA means that once branches are formed, they cannot be re-adjusted, which may lead to oversimplification in cases where subtle variability exists between sites.

K-means clustering, on the other hand, offered a more robust and dynamic approach. Its neural network origin and iterative optimisation process make it well suited for handling larger, multidimensional datasets where complex patterns are present. The method was particularly effective in differentiating sites with similar overall PBDE concentrations but distinct compositional profiles, providing sharper resolution of contamination sources. Its conceptual link to deep learning methodologies underscores its adaptability, as k-means can be integrated with more advanced machine-learning frameworks for predictive modelling of contaminant behaviour.

In practical terms, HCA excels as an exploratory, easy-to-visualise tool, while k-means provides deeper insights and higher resolution in clustering outcomes. When applied together, they complement one another: HCA offers interpretability and simplicity, while k-means adds precision and adaptability. This combined application ensures that both general patterns and finer-scale distinctions are captured, thereby enhancing the reliability of hotspot identification and supporting more informed decision-making in sediment monitoring and management.

CONCLUSIONS

This study confirmed the heterogeneous distribution of PBDEs in Serbian Danube sediments, with concentrations reaching up to 31.21 μg/kg d.w. and BDE-209 consistently dominating the congener profile. Such findings highlight the continuing environmental presence of deca-BDE mixtures, with additional contributions from lower-brominated congeners pointing to both historical use and possible debromination processes.

The application of hierarchical cluster analysis (HCA) and k-means clustering provided complementary insights into contamination patterns. HCA offered a clear, hierarchical grouping of sites that was valuable for visualising general similarities and identifying broad categories of contamination. In contrast, k-means—drawing on neural network learning principles—yielded higher resolution in cluster formation, allowing subtle differentiation between sites with comparable ΣPBDE levels but distinct compositional signatures. This demonstrated greater sensitivity to variability and enhanced the ability to distinguish among contamination sources and pathways.

By integrating classical statistical techniques with advanced machine-learning approaches, this study demonstrated a methodological framework that strengthens hotspot identification and prioritisation in environmental monitoring. Such combined analyses not only improve the interpretation of current contamination status but also create a foundation for predictive modelling of pollutant dynamics in large, complex river systems. From a management perspective, the identification of hotspots at Neštin, D6, and D10 underscores the need for targeted surveillance, remediation planning, and stricter control of PBDE inputs, particularly from waste and industrial sectors.
Overall, the study shows that bridging traditional multivariate analysis with neural network-based clustering can enhance both the interpretability and the analytical power of sediment contamination assessments. Future work should extend this integrative approach to larger datasets and additional pollutants, enabling more comprehensive risk evaluation and evidence-based decision-making for the protection of riverine ecosystems and human health.

Acknowledgements

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REFERENCES

[1] Förstner U., Wittmann G.T.W. Metal Pollution in the Aquatic Environment. Springer, 2012.
[2] Burton G.A. Sediment Toxicity Assessment. CRC Press, 2018.
[3] Eggleton J., Thomas K.V. A review of factors affecting the release and bioavailability of contaminants during sediment disturbance events. Environ. Int., 30 (2004): 973–980.
[4] Darnerud P.O. Toxic effects of brominated flame retardants in man and in wildlife. Environ. Int., 29 (2003): 841–853.
[5] Costa L.G., Giordano G. Developmental neurotoxicity of PBDEs: mechanisms and implications. Environ. Int., 38 (2012): 212–222.
[6] Law R.J., Covaci A. Brominated flame retardants in the environment. Environ. Int., 29 (2003): 725–734.
[7] Brborić M. et al. Unveiling the impact of lipophilic brominated flame retardants in Danube River sediments. EQA — Int. J. Environ. Quality, 71 (2026): 51–60.
[8] Brborić M. et al. Tracking brominated flame retardant patterns in Danube bottom sediment: multivariate statistical approach. Proc. MechEng XXI, 2023.
[9] Jain A.K. Data clustering: 50 years beyond K-means. Pattern Recognition Letters, 31 (2010): 651–666.
[10] Goodfellow I., Bengio Y., Courville A. Deep Learning. MIT Press, 2016.

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A VISUAL APPROACH TO PROJECT MANAGEMENT USING REACT FLOW

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Abstract: This paper presents the development of a graph-based project management tool that provides a visual and interactive representation of tasks, sections, and dependencies. The system is implemented using React Flow and custom components, enabling users to define project activities, assign responsibilities, and dynamically adjust dependencies. Unlike traditional approaches that rely on static charts, this tool emphasizes modularity and real-time interaction, offering visualization of individual tasks as well as aggregated sections, supported by forms for data entry. The implementation details include node structures for tasks and sections, edge customization for highlighting dependencies, and aggregation logic for calculating section durations. The solution demonstrates how modern web technologies can support intuitive project visualization and offers potential directions for extending the system with advanced features such as resource allocation and progress tracking.
Key words: Project management, React, React-Flow

INTRODUCTION

Project management is a critical aspect of both industrial and educational contexts, requiring careful planning, coordination, and monitoring of tasks and resources [1]. Despite the availability of numerous commercial and open-source tools, many existing solutions are either too complex for small teams or lack clear visualization of project flows and dependencies [2]. This can make understanding the overall project structure challenging, particularly for educational or research purposes.

The main objective of this work is to develop an interactive, graph-based project management tool that combines simplicity of use with basic project planning functionalities. The proposed solution leverages a modular design, representing tasks and sections as individual components, with dependencies visualized through interactive connections. By providing a clear overview of project structure and enabling dynamic modifications, the tool aims to support both learning and experimentation in project management scenarios.

In this paper, existing solutions for project management and visualization are reviewed, highlighting their strengths and limitations. Based on these observations, the motivation for developing a custom tool is outlined. The following sections present the user interface elements of the system, as well as key parts of the code implementation that enable interactive project planning and visualization.

As an illustrative example, the system is applied to a project involving the installation of solar panels, providing a concrete demonstration of the tool's capabilities.

PREVIOUS WORK

In the field of project management, a wide range of commercial and open-source tools are used in both industrial and educational contexts. Traditional software packages, such as Microsoft Project [3] and Primavera [4], represent industry standards and provide detailed planning, resource tracking, and management of dependencies among activities [2]. However, these tools often require significant training and can be overly complex for small teams or educational purposes [2].

With the rise of agile methodologies and collaborative work, tools like Jira [5], Trello [6], and Asana [7] have emerged, facilitating task tracking and team collaboration. While these tools

offer flexible and visually clear representations, their primary focus is on task management, and the visualization of overall project flows and dependencies remains limited.
In parallel, visualization tools such as Draw.io [8], Miro [9], and Lucidchart [10] enable users to create diagrams and graphs easily. These tools provide flexibility in representing processes, but they do not include project management logic, such as calculating task durations, critical paths, or resource allocation.
Additionally, Business Process Model and Notation (BPMN) tools, such as Bizagi [11] and Camunda [12], focus on modeling business processes. They allow detailed visualization of activity flows and dependencies but are not primarily intended for project management in educational or research contexts.
Based on the analysis of existing solutions, there is a clear opportunity for developing a tool that combines the simplicity of visual representation with basic project management functionalities. This concept forms the basis of the proposed software solution, which leverages the React Flow library to provide interactive visualization of project flows while maintaining minimal learning effort and maximum clarity.

THEORETICAL BACKGROUND

The theoretical background section provides the foundation for understanding the key concepts and technologies used in this work. It introduces essential principles of project management, including task organization, dependencies, and project planning techniques. Furthermore, it presents the technologies employed for implementing the proposed solution, with a focus on React and the React Flow library. Finally, this section outlines how these concepts are applied to the illustrative project example, highlighting the benefits of interactive and visual representation for project management.

Project Management

Project management is a structured approach to planning, organizing, and controlling resources to achieve specific objectives within a defined timeframe [1, 13]. A project is typically composed of multiple activities or tasks, each with a defined start and end point, dependencies on other tasks, and associated resources [1,13]. Key concepts include task sequencing, critical path, and Work Breakdown Structure (WBS), which help in organizing complex projects into manageable components [1, 13].
A particularly important aspect of project planning involves network-based methods, such as Critical Path Method (CPM) and Program Evaluation and Review Technique (PERT) [1, 14, 15, 16]. These methods use directed graphs to represent activities and their dependencies, making it possible to identify the longest sequence of dependent tasks that determines the overall project duration [1, 16]. Recognizing the critical path helps project managers focus on activities that directly impact project completion time, while also enabling the identification of time reserves (slack) in non-critical tasks [1, 16].
Visualizing projects through such network diagrams plays a crucial role in understanding task relationships and identifying potential bottlenecks. While Gantt charts primarily emphasize the timing and duration of tasks [17], network-based visualizations highlight task dependencies and the logical flow of activities [16], making alternative paths easier to identify. This makes them particularly valuable for both industrial and educational contexts, where clarity of relationships between tasks is essential. Studies have shown that interactive and visual tools based on network concepts improve comprehension and facilitate collaboration, particularly in educational and research environments [18, 19, 20].
By combining these principles with modern visualization techniques, it becomes possible to create a tool that is both easy to use and effective in conveying the structure and flow of projects. The proposed solution builds on these ideas by offering an interactive environment where project tasks are represented as nodes, dependencies as edges, and users can dynamically explore project structure in an intuitive manner.

React

React is a widely used JavaScript library for building interactive user interfaces, particularly in web applications [21]. Its component-based architecture allows developers to create modular and reusable elements, which can be combined to construct complex applications [21, 22].
In the context of this work, React provides the foundation for building an interactive project management tool. By leveraging components, it is possible to represent each task, user, or connection as an independent element, which can be easily modified or extended. This modularity enhances maintainability and simplifies the implementation of dynamic features, such as real-time updates of project status, drag-and-drop functionality, and interactive visualization of task dependencies.
Furthermore, React's integration with modern libraries enables seamless incorporation of visualization frameworks, such as React Flow, providing the necessary tools to represent project workflows in a clear and interactive manner. This combination allows users to intuitively understand project structure and manage tasks effectively, without being overwhelmed by the complexity often found in traditional project management software.

React Flow

React Flow is a JavaScript library built on top of React that enables the creation of interactive, node-based diagrams [23]. It allows developers to represent complex relationships visually, using nodes to symbolize entities or tasks, and edges to depict dependencies or flows between them.
In the context of project management, React Flow provides an intuitive way to visualize the structure of a project. Each task or activity can be represented as a node, with edges indicating dependencies such as "predecessor-successor" relationships. Users can interact with the diagram through drag-and-drop functionality, dynamically rearranging tasks or modifying connections, which enhances understanding and decision-making [23].
One of the key advantages of React Flow is its modularity and extensibility. Custom node types, styles, and interactive behaviors can be easily integrated, allowing for project-specific adaptations, such as color-coding tasks by priority, highlighting critical paths, or dynamically calculating project duration based on dependencies [23]. This flexibility makes it particularly suitable for educational and research applications, where simplicity and clarity are crucial, while still providing an accurate representation of project workflows.
By combining React's component-based architecture with React Flow's graph visualization capabilities, it becomes possible to create a project management tool that is both highly interactive and visually intuitive, making complex project structures easier to comprehend and manage.
The following section presents the implementation of these concepts in an interactive project management application.

IMPLEMENTATION

The application is structured as a graph-based project management tool. Tasks and sections are represented as nodes, with dependencies modeled as edges. Each task stores attributes such as duration and assigned team, enabling aggregation and visualization. The system was implemented using React Flow for interactive graphs, along with custom components for data entry and role assignment.

User Interface

The application interface is designed to support both visualization and project data management. Its central element is the project graph, where sections and tasks are represented as nodes, and their dependencies as edges. Tasks are visually distinguished by

color according to the assigned name or role, while section nodes provide a higher-level grouping of activities. This layout enables a clear overview of the project structure and makes navigation smoother. An example of these features is shown in Figure 1.

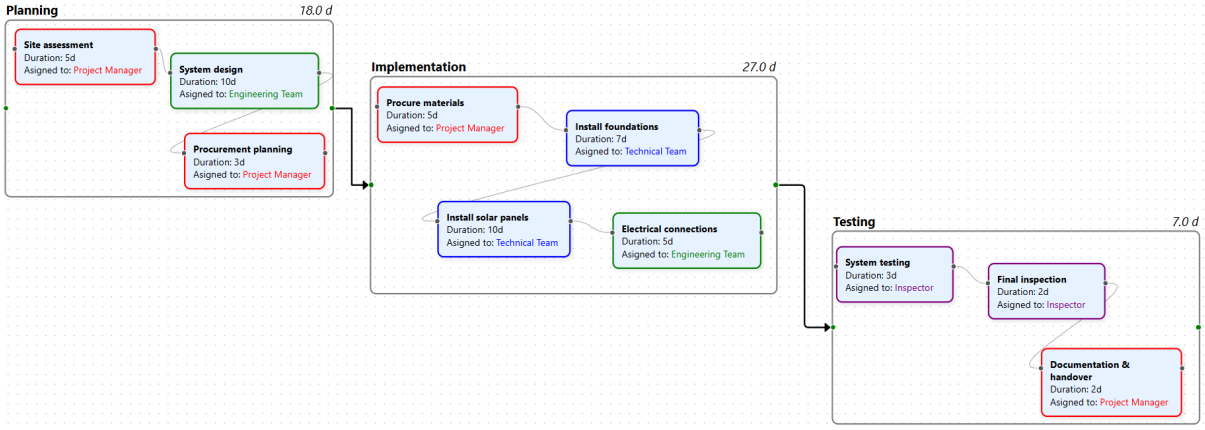


Fig. 1. *Example of a project plan*

The figure illustrates the complete project as represented in the application, including the Planning, Implementation, and Testing sections. Each section contains its respective tasks, clearly indicating task durations and assigned teams.
A form is provided for adding new tasks to the project. The user can specify the task name, duration, time unit, and the team member responsible for its execution. This ensures that all relevant details are captured and visualized appropriately in the project layout. An example of this form is shown in Figure 2.

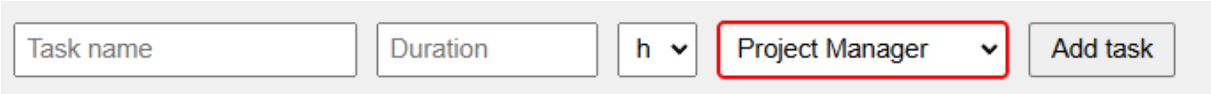


Fig. 2. *Form for adding tasks*

Another form allows the addition of new team members. The user can enter a name and choose a color from drop-down menu for visual identification in the project. This helps to organize and distinguish between contributors within the project view. It is a rather simple form, and example is shown in Figure 3.



Fig. 3. *Form for adding asignees*

Code Implementation

The project's interactive functionality is realized through modular React components, each responsible for representing specific elements of the project. Task nodes, section nodes, and form components work together to provide a dynamic and intuitive interface for project visualization and management.

The TaskNode component represents an individual task within the project. It encapsulates all relevant information about a task, including its name, duration, assigned team member, and visual style, such as color and border. Task nodes also provide handles for connecting to other

nodes, enabling the representation of task dependencies through edges. This modular design allows each task to be self-contained, making it straightforward to modify or extend task properties without affecting other components. Listing 1 illustrates the structure of a TaskNode component, showing how task details are displayed and how handles are included for connecting tasks.

```
<div>
    <div>
        <strong>{name}</strong>
    </div>
    <div>
        Duration: {duration}{unit}
    </div>
    <div>
        Asigned to: <span style={{ color }}>{assignee}</span>
    </div>
    <Handle type="target" position={Position.Left} style={{ background: "#555" }} />
    <Handle type="source" position={Position.Right} style={{ background: "#555" }} />
</div>
```

Listing 1. *Source code for TaskNode component*

Dependencies between tasks are represented using edges, which connect source and target handles on TaskNodes. These edges indicate the order of task execution and help visualize the flow of the project. Each edge can be customized with visual attributes, such as color, thickness, and arrow style, to improve clarity and distinguish between different types of dependencies.

Listing 2 shows an example of an edge connecting two sections.

```
{
  id: 'section-2-section-3',
  source: 'section-2',
  target: 'section-3',
  markerEnd: { type: MarkerType.ArrowClosed }
}
```

Listing 2. *Structure of an edge*

For section-to-section edges, the type is set to "smoothstep" to create a visually appealing curved connection, and the stroke width is increased to make these edges more prominent than standard task-to-task connections.

The SectionNode component represents a group of related tasks within the project. Each section node aggregates the tasks it contains, calculating the total duration based on the durations of its child tasks. Visually, section nodes provide a higher-level overview, making it easier to understand the structure and timeline of the project. Although the visual style is similar to task nodes, section nodes summarize information rather than focusing on individual task details.

To determine the total duration of a section, the SectionNode component iterates over all contained TaskNode components. It reads each task's duration and unit of time, converting them to a standard unit before summing. This ensures that tasks specified in different units, such as hours or days, are correctly accounted for in the section's total duration. By doing so, the SectionNode provides an accurate summary of the workload for the section, without the need to inspect individual tasks.

The function that checks whether a task belongs to a section evaluates the positions and dimensions of both the task and section nodes. This ensures that each section aggregates only the tasks that are visually contained within its bounds, and correctly calculates total duration with unit conversion. Described function is shown in listing 3.

```
const isTaskInsideSection = (taskNode, sectionNode) => {
  const [sx, sy] = [sectionNode.position.x, sectionNode.position.y];
  const [sw, sh] = [sectionNode.style?.width || 500, sectionNode.style?.height || 300];

  const [tx, ty] = [taskNode.position.x, taskNode.position.y];
  const [tw, th] = [taskNode.style?.width || 150, taskNode.style?.height || 50];

  return tx >= sx && ty >= sy && tx + tw <= sx + sw && ty + th <= sy + sh;
};
```

Listing 3. *Function to determine if a task belongs to a section*

Form components interact directly with the project graph, allowing users to add new tasks and team members. When a task or assignee is added through the corresponding form, the graph updates dynamically, reflecting the changes in real time. This integration ensures that all project data remains consistent and immediately visible, providing an intuitive link between data entry and project visualization.
This modular approach ensures that the project's structure can be easily extended and modified, while keeping the codebase organized and maintainable.

CONCLUSION AND FURTHER WORK

The developed project management tool provides an interactive and visual approach to planning and monitoring tasks within a project. By combining React with React Flow, the application allows users to clearly see task dependencies, section groupings, and overall project structure, while maintaining an intuitive interface for adding tasks and team members. The tool was demonstrated on the example of a solar panel installation project, where it enabled a clear and structured representation of all tasks and sections, making the overall plan more transparent and easy to follow.
Further improvements could include the integration of resource management, automatic calculation of critical paths, and support for additional task attributes, such as priorities or deadlines. Moreover, enhanced visualization features, such as filtering, or dynamic highlighting of critical tasks, could improve usability for larger projects. In addition, extending the system to support financial aspects such as costs and expenses would provide a more comprehensive project overview. Expanding the tool to support collaborative multi-user environments and real-time updates would further align it with modern project management practices and research-oriented use cases.

REFERENCES

[1] Kezner, Harold, "Project Management: A Systems Approach to Planning, Scheduling, and Controlling" (2025), Wiley, Hoboken
[2] Magrea, Romeo, Magrea, Camelia, "Open Source Approach to Project Management Tools" (2011), Informatica Economica vol. 15
[3] Microsoft Project, URL: https://learn.microsoft.com/en-us/project/
[4] Primavera, URL: https://www.oracle.com/construction-engineering/primavera-p6/
[5] Jira, URL: https://www.atlassian.com/software/jira
[6] Trello, URL: https://trello.com/
[7] Asana, URL: https://asana.com/uses/project-management
[8] Draw.io, URL: https://www.drawio.com
[9] Miro, URL: https://miro.com
[10] Lucidchart, URL: https://www.lucidchart.com/
[11] Bizagi, URL: https://www.bizagi.com/
[12] Camunda, URL: https://camunda.com/
[13] A Guide to the PROJECT MANAGEMENT BODY OF KNOWLEDGE (PMBOK Guide) (2017), Project Management Institute, Inc.

[14] Bishnoi, Nisha, "Critical Path Method (CPM): A Coordinating Tool (2018), Managt Sci Tech, International Research Journal of Management Science & Technology
[15] Bianconi, Francesco, "PERT Diagrams" (2024), Data and Process Visualisation for Graphic Communication. Springer, Cham.
[16] Agyei, Wallace, "Project Planning And Scheduling Using PERT And CPM Techniques With Linear Programming: Case Study" (2015), International Journal of Scientific & Technology Reasearch
[17] K, K, Ramachandran, K, K, Karthick, "Gantt Chart: An Important Tool of Management" (2019), International Journal of Innovative Technology and Exploring Engineering
[18] Zoss, Angela, Maltese, Adam, Uzzo, Stephen, Borner, Katy, "Network visualisation literacy: Novel approach to measurement and instruction" (2018), Network Science In Education. Springer, Cham.
[19] Kuosa, Kirsi, Distante, Damiano, Tervakari, Anne, Cerulo, Luigi, Fernandez, Alejandro, Koro, Juho, Kailanto, Meri, "Interactive Visualization Tools to Improve Learning and Teaching in Online Learning Environments" (2016), International Journal of Distance Education Technologies
[20] Brugliera, Patrick, "The Effectiveness of Digital Learning Platforms in Enchancing Student Engagement and Academic Performance (2024), Journal of Education, Humanities and Social Research
[21] Gackenheimer, Cory, "Introduction to React" (2015)
[22] Osmani, Andy, "Learning JavaScript Design Patterns", O'Reilly Media (2023 – Second Edition)
[23] Official React Flow documentation, URL: https://reactflow.dev/

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HYBRID MODEL APPROACH FOR PRODUCT LEVEL DEMAND FORECASTING IN RETAIL

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Abstract : In this study, store level sales time series were analyzed to improve demand forecasting in the retail sector. Raw sales data were indexed by date and enriched with covariates such as holidays, weather, promotions, and seasonality. Using these datasets, models including Prophet, EMA, CatBoost, N-HiTS, and Temporal Fusion Transformer (TFT) were evaluated. A systematic selection process identified the most accurate model for each store–product combination. Results show that statistical models perform well for linear demand patterns, while deep learning approaches better capture complex seasonal and promotional effects. By proposing a hybrid evaluation framework, this study contributes to the literature and offers a practical method for stock optimization and operational decision support .**Key words:** Machine Learning, Deep Learning, Classical Models, Demand Forecasting, Hybrid Application

INTRODUCTION

Demand forecasting with artificial intelligence (AI) models is widely utilized and continuously developed today by companies of all sizes operating in the retail sector. By leveraging demand forecasting, companies engaged in delivery services can determine courier wages based on regional demand levels, restaurants can adjust their prices according to demand at specific hours, supermarket chains can regulate the distribution of products to their branches in line with expected demand, and many similar applications can be implemented to safeguard the interests of customers, employees, and companies alike.

The Aim Of The Study

In this study, the objective is to forecast the sales quantities of every combination of different products across different stores by employing hybrid models within a single unified framework.

Contributions Of The Study

This study presents a hybrid demand forecasting system by integrating statistical and AI-based methods, which are often addressed separately in the literature, into a single framework. Traditional methods (e.g., EMA, Holt-Winters) produce fast and efficient results for products with low variance and simple trends, while advanced machine learning and deep learning–based methods such as CatBoost, N-HiTS, and Temporal Fusion Transformer (TFT) demonstrate superior performance on complex series enriched with external factors such as promotions, holidays, and weather conditions. The main contributions of the study can be summarized as follows:

- **Hybrid Model Framework:** A scalable structure has been developed that integrates statistical and AI-based methods, allowing the automatic selection of different forecasting models according to series-level complexity.

- **Comprehensive Data Integration:** Beyond sales data, holidays, promotions, and weather information were systematically integrated into the model, enhancing the explanatory power for demand fluctuations.

- **Large-Scale Implementation:** An efficient data preparation pipeline was designed to process millions of sales records; through the use of Parquet format and chunk based processing techniques, both memory management and processing times were optimized.

- **Real-World Validation:** The modeling approach was tested on store–product level sales data from a large-scale retail chain, demonstrating its direct applicability to operational decision support processes.

These contributions not only introduce a novel hybrid modeling approach to the academic literature but also provide a practical solution for critical areas in the retail sector such as inventory management, pricing, and logistics planning.

RELATED WORKS

Traditional Demand Forecasting Methods

In time series forecasting, classical models such as ARIMA and Exponential Smoothing (ETS) have generally been at the forefront since the early stages. These models consider the sales history of each product separately and capture trend and seasonality in a relatively simple manner, usually under linear assumptions.

For instance, *Auto Regressive Integrated Moving Average (ARIMA)* combines autoregression, differencing, and moving average components to capture underlying demand and seasonal effects [1]:

$$\boldsymbol{\Phi p(B)(1 - B)dyt = \Theta q(B)\varepsilon t}(2)$$

where B is the backshift operator, d the order of differencing, and $\Phi_p(B)$ and $\Theta_q(B)$ represent the autoregressive and moving average polynomials, respectively.

Although these types of methods perform well for series with simple and regular demand structures, they are limited in their ability to model external factors such as holidays, promotions, or weather conditions, and often fall short in large-scale retail applications.

Traditional Demand Forecasting Methods

Recent advances in machine learning and global modeling have greatly improved demand forecasting by handling numerous covariates and capturing nonlinear relationships. Global models can train on thousands of product–store series simultaneously, extracting shared patterns [2]. In the M5 Forecasting Competition, top teams successfully applied gradient-boosted models like LightGBM to forecast large sets of series under one global structure [3]. These methods also integrate external factors such as weather, promotions, and holidays, achieving lower error rates than classical approaches [4], [5], with reported error reductions exceeding 40%.

Advanced Deep Learning Models

Deep learning methods, especially Transformer-based architectures, have achieved state-of-the-art results in time series forecasting. Unlike LSTM and GRU networks, which capture short-term dependencies but struggle with long sequences and training stability [6], Transformers leverage self-attention to model long-term dependencies more effectively, improving accuracy on retail datasets [7], [8]. The Temporal Fusion Transformer (TFT), for instance, jointly processes static, historical, and future covariates while offering interpretable variable importance [7]. Likewise, N-HiTS employs a multi-scale architecture that enhances long-term

stability [9]. Gradient-boosted models such as CatBoost also remain competitive, flexibly capturing promotion and calendar effects in large-scale retail data [10].

Summary And Positioning Of Our Study

In light of these developments in the literature, our study proposes a hybrid forecasting framework. For series with low variance and simple trends, statistical methods such as EMA and Holt–Winters are preferred, while for complex, seasonal, and volatile series, advanced machine learning and deep lear- ning–based models such as TFT, N-HiTS, and CatBoost are employed.

For example, the *Exponential Moving Average (EMA)* summarizes the past by assigning exponentially decreasing weights to each new observation:

$$\hat{y}t = \alpha yt - 1 + (1 - \alpha)\hat{y}t - 1,0 < \alpha < 1 \qquad (3)$$

This approach provides a fast and computationally inexpensive method, particularly for low-variance series.

In contrast, the *Temporal Fusion Transformer (TFT)* model leverages *attention* mechanisms to capture multivariate and long-term dependencies. In simplified form, the weights of past time steps $\alpha_{t,i}$ are normalized using the softmax function, and a contextual summary is generated for each step:

$$z_t = \sum_{i=1}^{T} \alpha_{t,i} \cdot h_i, \quad where \quad \alpha_{t,i} = exp(e_{t,i}) / \sum_{j=1}^{T} exp(e_{t,j}) \qquad (4)$$

where h_i denotes the past hidden states and $e_{t,i}$ the learned attention scores. Thus, rather than relying only on the most recent observations, TFT can selectively focus on critical points throughout the entire history, enabling it to capture complex seasonal and external effects.

Furthermore, the systematic integration of external covariates such as holidays, weather conditions, and promotions represents a key distinction that enhances forecasting accuracy compared to existing literature. In this way, our study not only contributes to the academic literature by introducing a hybrid model selection framework but also offers a practical method for inventory optimization and operational decision support systems in the retail sector.

BACKGROUND

Developing a hybrid AI-based demand forecasting system requires several preparatory steps. Each model undergoes data preprocessing tailored to its parameters, and error metrics are applied to prevent overfitting. To improve forecast accuracy, hyperparameters are optimized using tools such as Optuna. Moreover, to ensure consistency across models, all processes are executed within the same version of the Darts library.

Data Preparation Step

In the demand forecasting process, data preparation is one of the most critical stages that directly influences model performance. The sales data used in our study were obtained in the form of large CSV files at the gigabyte scale. Since it is not feasible to process data of this size directly in memory, the files were divided into parts using a *chunk* approach and subsequently converted into Parquet format. The Parquet format not only reduced storage requirements through its compression capability but also enhanced operational efficiency by enabling faster data access during training. In this way, millions of rows of raw sales records were transformed into a manageable structure.

In the data preparation process, not only the raw sales quantities but also external and derived covariates that can enhance forecast accuracy were incorporated into the dataset. The covariates used can be summarized under the following categories:

- **Time-Based Features:** Lagged sales values (y_{t-7}, y_{t-14}, y_{t-28}) and moving averages were added to model historical trends and short-term dependencies.
- **Calendar Features:** Official holidays (*holidayDays*) and weekends (*weekend*) are critical for capturing regular sales fluctuations in the retail sector.
- **Weather Conditions:** Binary variables representing rainy (*rainyWeather*), snowy (*snowyWeather*), and sunny (*sunnyWeather*) days are particularly useful for expl ining seasonal and regional demand fluctuations
- **Promotion Information:** Campaigns applied on specific dates (*promotion*) serve as important covariates to explain sudden sales spikes, especially for volatile products.
- **Static Covariates:** Time-invariant information such as store code, city code, and product ID (*static covariates*) enables training multiple stores and products under the same model.

Covariate processing varies by model: EMA and Holt–Winters rely solely on past sales, Prophet adds calendar effects, and CatBoost flexibly handles categorical factors such as holidays, promotions, and weather. Deep learning models can integrate past, future, and static covariates to capture complex seasonal and external influences, with TFT jointly processing past and future inputs and N-HiTS excelling at past-dependent short- and medium-term forecasts. These complementary strategies enable the hybrid framework to systematically match each store–product pair with the most appropriate model based on covariate relevance.

Table 1. *Use Of Covarities By Model*

Model	Past Covariates	Future Covariates	Static Covariates
EMA / Holt–Winters	no	no	no
Prophet	Limited (trend/seasonality)	no	Holidays and special days
CatBoost	yes (lag features)	no	yes (holidays, promotions, weather)
TFT	yes	yes	yes
N-HiTS	yes	no	yes
N-BEATS	yes	no	limited
TiDE	yes	yes	yes
DLinear	yes	yes	optional
TSMixer	yes	yes	yes

Preventing Overfitting

Overfitting is defined as a forecasting model memorizing patterns in the training data and consequently showing poor generalization performance on new data. In this study, multiple methods were applied simultaneously to prevent overfitting.

First, all models were evaluated separately with training and validation (*validation*) datasets. In particular, for deep learning models such as TFT, N-HiTS, and TiDE, validation errors were closely monitored, and an early stopping (*early stopping*) algorithm was employed. Training was automatically terminated according to a specified (*patience*) value whenever the validation error failed to improve beyond a certain threshold.

$$Stop\ if\ Lval(t) \geq Lval(t-k) - \Delta\ \forall\ k \in \{1,2,\ldots,p\}. \quad (5)$$

The early stopping mechanism, defined by a patience value **p** and a minimum improvement threshold **Δ**, prevents overfitting by halting training once progress stalls, thereby preserving generalization. Since complex machine learning models are especially prone to overfitting due to richer parameterizations and covariate exploitation, several safeguards were applied: limiting the number of covariates, using dropout, and incorporating regularization strategies such as weight decay and learning rate scheduling.

$$\tilde{\boldsymbol{h}}(l) = \boldsymbol{m}(l) \odot \boldsymbol{h}(l), \boldsymbol{m}(l) \sim Bernoulli(p) \quad (6)$$

Dropout randomly deactivates a subset of neurons during training.

On the other hand, in simple series where statistical models such as EMA or Holt–Winters are used, the risk of overfitting was inherently low. In contrast, for more flexible models such as CatBoost and TFT, error metrics (MAE, MAPE, RMSE) were continuously monitored, and the configurations yielding the lowest generalization error were selected.

Model Optimization
Model hyperparameters were tuned using Optuna and Mango Tuner, which explore parameter combinations in a controlled simulation environment by training models at each trial and evaluating validation errors. Mean Absolute Error (MAE) served as the primary loss function, with RMSE and MAPE applied when needed. Optuna employed adaptive search strategies and pruning to terminate unpromising trials early, while Mango Tuner provided a faster, lightweight scan of parameter ranges for models such as N-BEATS, TiDE, and DLinear. The best-performing combinations were then retrained, ensuring a reproducible and standardized optimization process across model families.

METHODOLOGY

In this section, the different models used in the experimental process of the study and their training phases are explained in methodological detail. The characteristics and strengths of each model, optimized for different configurations, are also highlighted.

Models Used

The forecasting methods employed in this study are classified into three main groups: (i) traditional statistical methods, (ii) machine learning–based methods, and (iii) deep learning–based methods. The theoretical background, working principles, and role in the forecasting process of the models used under each group are explained below.

1)Traditional Statistical Methods: Preferred for low-variance series with simple trend/seasonality.

Exponential Moving Average (EMA) : No training; exponentially weighted past values provide a strong baseline for stable, momentum-driven series. Ignores covariates, so external effects aren't captured; also used as a reliable fallback.

Holt–Linear : Univariate exponential smoothing with level+trend; captures simple linear trends absent in EMA but still no covariates.

Holt–Winters Exponential Smoothing / ETS : Extends Holt by adding seasonality; effective for weekly cycles with limited external shocks.

Prophet : Flexible trend (linear/logistic) + Fourier seasonality + holiday/special day regressors; configured simply for fast forecasts across store–product pairs.

2)Machine Learning–Based Methods: Mid-complexity models with covariates for series showing moderate external effects.

CatBoost : Handles categorical/binary drivers (holidays, promotions, weather) and lags efficiently via gradient-boosted trees. Hyperparameters (lags, depth, learning rate, iterations) tuned (e.g., Optuna). Outperforms classical models where exogenous factors dominate.

3)Deep Learning–Based Methods: Suited to complex patterns, long dependencies, and multiple covariates.

Temporal Fusion Transformer (TFT): Jointly uses past, future, and static covariates; regularized (e.g., dropout/weight decay, LR scheduling) with early stopping and MAE/RMSE/MAPE monitoring. Excels at combining seasonality with external drivers (promotions, weather).
N-HiTS : Multi-scale blocks for accurate long horizon forecasts; robust on scaled series.
N-BEATS: Backcast–forecast blocks that disentangle trend/seasonality; strong univariate reference, less reliant on external inputs than TFT.
TiDE: Encoder–decoder effective for long multivariate horizons; sensitive to windowing/scaling choices.
DLinear: Simple linear projections for long horizons; fast and low-overfit risk, but limited with nonlinear/exogenous effects.
TSMixer: Lightweight mixing of multivariate inputs; tuned (e.g., blocks/hidden size/dropout with Mango). Efficient for short–medium horizons and regular patterns but can lag under high-frequency shocks.

Model Selection Strategy

In this study's hybrid framework, the ModelManager component evaluates all forecasting models for each store–product pair using error metrics (MAE, RMSE, MAPE) and selects the one with the lowest error. This ensures forecasts are as close as possible to actual demand totals. Simple models like EMA or Holt–Winters are chosen for stable, low-variance series, while advanced models such as CatBoost, TFT, or N-HiTS are applied to complex and volatile cases. The result is a flexible, adaptive system that tailors model selection to the heterogeneity of product demand.

RESULTS

In this section, the findings obtained during the experimental stages of the study are presented. In the first stage, the experimental results compare the backtesting outcomes at 7, 14, and 30 days for 100 products, where the models used in the application were trained separately with simplified parameters.

In the second stage, case studies conducted with the final versions of the models are presented, and the strengths of the hybrid model framework are discussed.
Finally, in the third stage, the computational and operational costs of the models used in the application are compared, and the advantages and limitations of each model for practical implementation are evaluated.

Overall Performance Comparison

Table 2. *Forecasting performance of models for selected products*

Model	Average MAE	Average RMSE
CatBoost (FitEach)	28.19	35.14
Exponential Smoothing	30.43	37.23
HoltLinear	31.59	38.63
EMA	31.13	37.80
HoltWinters	30.49	37.98
DLinear	32.93	40.73
TiDE	33.39	41.23
Prophet	38.50	47.02
TFT	54.89	85.94
N-BEATS	796.29	1266.68
TSMixer	84.10	115.74
N-HiTS	140.93	202.06

Table 2 reports average MAE and RMSE values for 7, 14, and 30-day horizons across 100 products. Under the simplified test setup, deep learning models (TFT, N-HiTS, N-BEATS, TiDE, TSMixer) produced higher errors than simpler methods, with N-BEATS showing notable instability. This indicates that complex models require larger datasets and careful tuning to outperform classical approaches.
CatBoost delivered the best overall performance, reflecting its balance between complexity and flexibility. Classical ETS methods, including Exponential Smoothing and Holt–Winters, also proved highly competitive, while EMA exceeded expectations as a strong baseline.

Case Study Analyses

Table 3. *Average MAE and RMSE, calculated by averaging 7, 14, and 30-day horizons*

Product	Sales Quantity	Forecasting Model	Difference (%)
Curly Lettuce Bunch	98,093	EMA	51.0
Parsley	160,134	Holt–Winters	4.0
Mandarin (kg)	39,525	TFT	34.0
Brand Cigarette Pack	34,346	Exp. Smoothing	2.0
Brand Packaged Cake	22,335	Prophet	7.0
Sandwich Bread (pcs)	167,734	CatBoost	5.0
Brand Cola 250ml	26,902	N-HiTS	41.0
Local Avocado	123,239	Holt–Linear	10.0
Bonito (fish)	22,974	TSMixer	27.0
Brand Cola 2.5L	16,168	CatBoost	17.0

Table 3 shows that hybrid model selection improves accuracy across product categories. For low-variance items with little external influence (e.g., lettuce, cigarette packs), simple methods such as EMA and Exponential Smoothing performed best. In contrast, products sensitive to seasonality or promotions (e.g., parsley, mandarins) benefited from Holt–Winters and TFT, while cola sales, strongly driven by campaigns,

were better captured by N-HiTS and CatBoost.
These findings highlight the hybrid approach's strength: classical models efficiently handle stable products, while deep learning and machine learning methods capture complex, externally influenced patterns, leading to overall performance gains.

CONCLUSION

This study developed a hybrid forecasting framework to improve demand prediction accuracy and operational efficiency in the retail sector. By systematically evaluating multiple model families for each store–product pair, the system selected the most accurate model favoring simple statistical methods for stable series and advanced models for complex, seasonal, or covariate rich series. This adaptive approach eliminates dependence on a single model and ensures forecasts are tailored to demand variability.
The results demonstrate that hybrid model selection contributes both to academic literature and to practical applications in inventory management, logistics planning, and decision support systems. Future work will extend the approach to larger datasets and other industries, while also exploring more efficient optimization techniques to reduce training times.

REFERENCES

[1] R. J. Hyndman and G. Athanasopoulos, Forecasting: principles and practice. OTexts, 2008.
[2] K. Bandara, C. Bergmeir, and H. Hewamalage, "Forecasting across time series databases using recurrent neural networks on groups of similar series: A clustering approach," in International Joint Conference on Neural Networks (IJCNN), 2020.
[3] S. Makridakis, E. Spiliotis, and V. Assimakopoulos, "The m5 accuracy competition: Results, findings and conclusions," International Journal of Forecasting, vol. 37, no. 4, pp. 1346–1364, 2021.
[4] I. Bose and X. Chen, "Integrating weather variables in demand forecas- ting models for retail," Decision Support Systems, vol. 137, p. 113366, 2020.
[5] R. Wen, K. Torkkola, B. Narayanaswamy, and D. Madeka, "A mul- tivariate time series forecasting model with covariates for retail de- mand," in International Conference on Learning Representations (ICLR) Workshop, 2020.
[6] N. Laptev, J. Yosinski, L. E. Li, and S. Smyl, "Time-series extreme event forecasting with neural networks at uber," in International Conference on Machine Learning (ICML) Time Series Workshop, 2017.
[7] B. Lim, S. Ö. Arik, N. Loeff, and T. Pfister, "Temporal fusion transformers for interpretable multi-horizon time series forecasting," in International Journal of Forecasting, vol. 37, no. 4, 2021, pp. 1748–1764.
[8] H. Zhou, S. Zhang, J. Peng, J. Zhang, Y. Li, and H. Xiong, "Fedfor- mer: Frequency enhanced decomposed transformer for long-term series forecasting," in International Conference on Machine Learning (ICML), 2022, pp. 27 268–27 286.
[9] B. Oreshkin, S. Carpov, N. Chapados, and Y. Bengio, "N-hits: Neural hierarchical interpolation for time series forecasting," in NeurIPS, 2021.
[10] A. V. Dorogush, V. Ershov, and A. Gulin, "Catboost: unbiased boosting with categorical features," in Advances in Neural Information Processing Systems (NeurIPS), 2018.

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DIGITAL PROMOTION PLANNING AND OPTIMIZATION: AN AI-POWERED RETAIL APPLICATION

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Abstract: This study aims to digitize and optimize promotion planning processes within a retail chain characterized by high promotional intensity. By replacing existing manual processes with an end-to-end automated system leveraging AI-powered recommendation engines, pricing algorithms, and ERP integrations, the entire workflow has been transformed.
Results from a pilot implementation demonstrate a 15% reduction in low-impact campaigns, a 12% increase in stock turnover rate, and an 8% increase in promotional profitability.
Keywords: Artificial Intelligence, Promotion Optimization, Machine Learning, Retail, Pricing

1. INTRODUCTION

Promotion planning is directly linked to sales, inventory, and profit management within the retail sector. In environments with high promotional intensity, reliance on manual decision-making processes often leads to errors and low efficiency. This study aims to digitize and automate promotion planning processes by utilizing historical data analytics and artificial intelligence algorithms.
The transition from manual to digital workflows enhances operational efficiency, minimizes errors, and accelerates processes. As part of this transformation, a data-driven promotion recommendation system was developed to enable more accurate decision-making and prevent the implementation of redundant or unprofitable promotions. Integration with ERP and point-of-sale (POS) systems ensures the consistency and reliability of data flow, while the system's continuous learning capability enables the generation of replicable campaigns. This approach supports both operational flexibility and sustainable profitability.

2. LITERATURE REVIEW

In contemporary promotion planning, artificial intelligence (AI) and machine learning (ML) approaches have become critical components of the decision-making process. Data analytics not only enables the measurement of past performance but also facilitates more accurate future demand and price forecasting. AI-powered systems analyze historical sales, inventory, and promotion data to predict which campaigns will yield the highest returns, and subsequently recommend optimal promotion strategies.
Time series modeling is one of the fundamental tools in this domain. Models such as Prophet, ETS, and LSTM are widely used for demand forecasting and price optimization. The Prophet model stands out for its ability to handle irregular and missing datasets, easily integrate holiday and seasonal effects, and provide interpretable outputs. This accessibility makes it a valuable tool for both data scientists and business units, allowing model outputs to be directly translated into operational decisions. While deep learning-based LSTM models offer high accuracy, particularly in big data environments, they require significant computational resources. Prophet offers a balanced approach in terms of speed, flexibility, and cost, making it a prominent choice for retail promotion planning.
AI plays a critical role not only in forecasting but also in optimization. Advanced methods like Bayesian Optimization are instrumental in determining the best promotion strategies within

multi-dimensional decision spaces, thereby enhancing campaign performance and mitigating low-impact promotions. These methods learn from prior iterations to narrow the search space, offering faster, more accurate, and more cost-effective solutions compared to traditional methods.
When these AI-based approaches are integrated with ERP systems, the process becomes end-to-end automated, reducing human error and accelerating decision cycles. As a result, promotion planning evolves from a retrospective analysis process into a proactive, predictive decision support system.

Research Gap and Our Contribution:

Most existing studies in the literature focus either on demand forecasting (e.g., with Prophet or LSTM models) or on price optimization alone. Furthermore, many of these studies overlook the critical aspects of ERP integration and end-to-end automation.
This study addresses these gaps by designing an integrated promotion recommendation system that combines both time series modeling and optimization techniques. Moreover, the direct integration of model outputs into the ERP system allows recommendations to be automatically implemented, eliminating manual steps. In this respect, the study unifies data analytics, AI-based forecasting, optimization, and process integration into a single platform, and presents quantitative results from a practical application.

Strategic Objectives and Expected Benefits

Table 1. *Strategic Objectives and Expected Benefits*

Strategic Objectives	**Expected Benefits**
Digital recommendation system	Increased accuracy and reduced errors
Optimization engine	Maximized profitability
ERP integration	Data consistency and process speed

3. METHODOLOGY

3.1 Data Sources and Preprocessing

For the system to function effectively, information from multi-dimensional sources—including sales, inventory, promotion, and competitor data—is utilized. This data is processed through batch or streaming ETL (Extract, Transform, Load) workflows, and its reliability is enhanced through data validation and missing data imputation. SKU matching and channel normalization integrate information from various sources, ensuring that analyses are consistent and comparable.
Furthermore, the protection of customer data during these processes is of critical legal and ethical importance. In accordance with data protection regulations such as GDPR, personal data is used only for specific purposes, protected against unauthorized access, and processed transparently. In promotion and price optimization processes, personally identifiable customer information is anonymized and masked. Explicit consent is obtained from customers for the use of their data, and data usage permissions are meticulously managed. These practices ensure that data analytics are conducted in a reliable manner that aligns with legal and ethical standards.

3.2 Modeling and Algorithms

The methodology begins with segmentation and similar SKU analysis using algorithms such as k-means and HDBSCAN. These methods group products with similar attributes, such as

those within the same category or exhibiting similar sales behavior. This enables more targeted and effective campaign planning.
The second step involves forecasting. Time series models such as Prophet, ETS, and LSTM are used to predict future demand and price movements. This allows for proactive planning by anticipating how much a product will sell or how a price change will affect sales. The flexible structure of the Prophet model allows for the inclusion of factors like holidays and seasonality in these forecasts.
Subsequently, we employ uplift and causal modeling. Methods like CausalForest and X-learner are used to analyze the impact of promotions on different customer segments. This allows us to determine if a promotion is effective for one group of customers but not another, enabling more personalized and effective campaigns.
Additionally, we conduct scenario and simulation studies. We test various campaign types in a computational environment to evaluate their outcomes. This helps answer questions such as whether a 10% discount or a bundle promotion is more effective, or how long a campaign should run.
We also perform elasticity analysis using methods like panel regression and Hierarchical Bayes to quantify how demand changes in response to price changes. This provides numerical answers to questions such as how much sales will drop if the price is increased, or how much they will rise if a discount is applied.
Finally, an optimization engine is deployed. It uses ILP (Integer Linear Programming), Bayesian Optimization, and other heuristic algorithms to synthesize all this information and determine the optimal campaign parameters. This allows for the most profitable selection of which products to discount, at what rate, and when to run the campaign.

Optimization Engine Workflow:

Retail promotion optimization studies are based on the simulation and evaluation of potential campaign scenarios at the SKU level (Smith & Lee, 2020; Lee, Chen & Brown, 2022). The system evaluates available campaign options for each SKU and calculates the estimated sales increase (uplift) and profitability. However, purely simulation-based methods have limited applicability as they often fail to account for real-world operational constraints.
In this study, the optimization approach has been restructured around an objective function and a set of constraints. The objective function is defined as the maximization of total profit or a specific KPI (e.g., sales volume, ROI) (Jones & Wang, 2019):

$$Maximize \sum_{i \in SKU} \sum_{j \in Promotions} (\text{Revenueij} - \text{Costij}) \times \text{DecisionVariableij}$$

The constraints considered in the optimization process are as follows:

- **Stock Constraint:** The estimated number of units sold cannot exceed the available stock.
- **Minimum Margin Constraint:** The difference between the selling price and the cost cannot fall below a predetermined minimum margin.
- **Budget Constraint (Optional):** The total promotional cost cannot exceed the allocated budget.
- Maximum Promotion Limit per SKU (Optional).

This framework allows campaign scenarios to be evaluated not only on estimated profit and sales uplift but also on operational criteria such as stock alignment, margin, and profitability (Kumar & Patel, 2021).

3.3 Decision and Workflow

The model provides the top three campaign recommendations for each SKU, along with a clear rationale. These recommendations are then approved sequentially by the category manager,

followed by the purchasing department, and finally by the finance department. All decisions are logged and version-controlled for historical tracking.

3.4 ERP and POS Integration

Campaign data is transferred to the ERP system (e.g., SAP) and validated at the point of sale (POS). Changes are first applied to a small test group to prevent errors before full deployment.

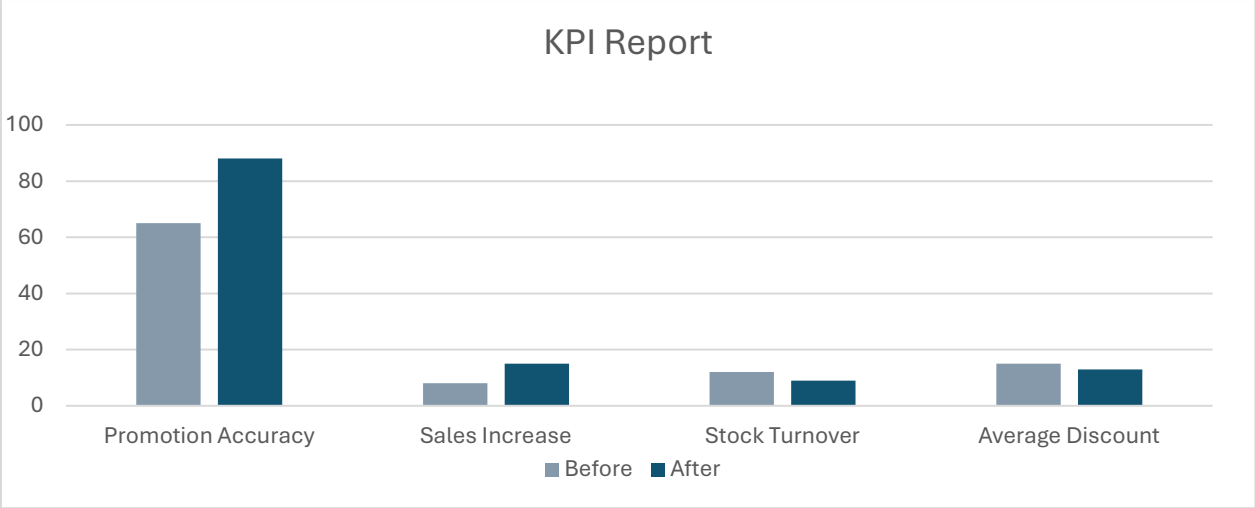
3.5 Monitoring and Feedback

Campaign performance is monitored using KPIs such as sales uplift, incremental revenue, profit margin, and sales velocity. These metrics are tracked via dashboards, and the model is retrained if its performance degrades.

4. APPLICATION AND PILOT STUDY

The effectiveness of the promotion planning and price optimization processes was evaluated through an AI-based recommendation system. The analysis was conducted on a sample of 5 stores and a total of 150 SKUs. The dataset covers the period from 2023-07-01 to 2025-07-30 and includes the following key columns: SKU ID, category, store ID, date, sales quantity, unit price, stock status, promotion type, and customer segment information.
The first 30 days of the dataset were used for model training, with the remaining 2 years of data (2023-07-31 to 2025-07-30) allocated as the test set. This long-term test set is crucial for measuring the model's ability to adapt to seasonality, holidays, and other periodic fluctuations. The total number of data points was calculated as 5 stores × 150 SKUs × 730 days ≈ 547,500 observations. Missing data, at a rate of 2%, was imputed using linear interpolation and store/product-based averages.
The AI-based recommendation system analyzes historical sales and inventory data to suggest optimal promotion and pricing strategies. System performance was tested based on forecast accuracy, promotion effectiveness, and operational KPIs. Prophet, ETS, and Random Forest algorithms were used as forecasting models to examine recommendation accuracy and adaptation to long-term scenarios. Furthermore, scenario and simulation studies were conducted to predict the impact of different discount rates, bundle campaigns, and temporary promotions on sales, revenue, and profitability.

Table 2. *Performance Comparison of the Manual System vs. the AI-Powered System*



5. DISCUSSION

The distinction between promotional and regular pricing is critical for accurately analyzing consumer behavior and effectively implementing pricing strategies (Smith & Lee, 2020; Lee, Chen & Brown, 2022). Considering the unique dynamics of different store formats enhances the system's applicability.

In existing manual systems, promotion approval processes and pricing decisions are typically lengthy, multi-step, and prone to error (Kumar & Patel, 2021). This not only reduces operational efficiency but also limits decision-maker confidence. The new system, with its user-friendly and interpretable approval mechanism, accelerates processes and builds trust. Structuring automation processes with recommendation, approval, and activation steps streamlines workflows and minimizes the risk of error, while also enabling the rapid implementation of decisions and effective monitoring of outcomes (Shahriari et al., 2016; Jones & Wang, 2019).

As shown in Table 3: Comparison of the Manual System vs. the New Automation-Supported System, significant gains are achieved with the new system. For example, the average sales increase in previous campaigns was 6%, whereas with the new system, this rate rose to 11%. These data confirm that data-driven and automation-supported processes provide critical advantages in retail promotion management.

Table 3. *Comparison of the Manual System vs. the New Automation-Supported System*

Criterion	**Manual System**	**New Automation System**
Campaign Approval Time	Average 7 business days	2 business days
Promotion Effectiveness Measurement	Measurement with limited data	Detaylı veri analizi (satış verileri, mağaza formatları, tüketici segmentleri)
Average Sales Increase	6% sales increase	11% sales increase
Analysis Detail	General-level analysis	Segment-based detailed analysis

This table demonstrates that analytics-based pricing and promotion management, supported by automation, provide distinct gains over manual systems in terms of both operational efficiency and sales performance (Taylor & Letham, 2018; Wager & Athey, 2018). Furthermore, tracking previous campaign performance provides concrete evidence of the new system's effectiveness; for instance, while the average sales increase in previous campaigns

was 5–7%, it rose to 10–12% with the new system. These data confirm that data-driven and automation-supported processes provide critical advantages in retail promotion management.

Despite the positive outcomes of this pilot study, detailed comparisons of the training processes, hyperparameter settings, and model performance for the underlying algorithms (Prophet, Causal Forest, Bayesian Optimization) were kept outside the scope of this paper. Future work should involve a deeper analysis of these technical details to enhance the system's transparency and reproducibility.

6. CONCLUSIONS AND EXPECTED GAINS

The implementation of this AI-powered system shortens the purchasing cycle and increases decision accuracy, thereby boosting operational efficiency. The reduction in low-impact campaigns ensures more efficient use of resources, while the increased stock turnover rate significantly mitigates the risk of excess inventory. Furthermore, balanced discount rates enhance sales volume while preserving profitability. ERP integration guarantees data consistency, enabling seamless and error-free processes. The ability for management to monitor real-time performance reports facilitates timely strategic decisions and more effective process control.

The main evaluation metrics that can be used to measure the system's effectiveness are as follows:

- Forecast/Recommendation Accuracy: Measures how accurately the system predicts future sales or campaign recommendations. Metrics such as MAE (Mean Absolute Error), RMSE (Root Mean Squared Error), and MAPE (Mean Absolute Percentage Error) are used for this purpose. For example, the forecasting error (MAPE) which was 15-18% with manual processes, has decreased to 7-10% with the automation-supported system.
- Promotion Effectiveness: Examines the real impact of the campaigns suggested by the system. Precision@k indicates the accuracy rate of the top k recommendations. Uplift Analysis measures the heterogeneous effects of promotions on different customer groups. ATE (Average Treatment Effect) and ATE CI (Confidence Interval) determine the average effect and confidence interval of the promotion. In a pilot test of 50 products, the promotion accuracy rate increased from 65% to 88% ($p < 0.05$, t-test).
- Operational Performance: Measures the value the system adds to business processes. Metrics such as campaign approval time, stock turnover rate, sales volume, and profitability are used. Compared to manual processes, a marked improvement in stock turnover rate and campaign performance is observed.

7. FUTURE WORK

The continuous optimization of machine learning models is a fundamental element in increasing the system's accuracy and effectiveness. In particular, regularly improving the performance of uplift and causal models enables a more precise measurement of campaign effects and a more accurate prediction of customer behavior. Additionally, implementing real-time price and stock optimization offers significant advantages in terms of both profitability and customer satisfaction, allowing for a swift and effective adaptation to dynamic market conditions.

Future research aims to conduct a more in-depth analysis of how the models are trained on larger datasets, the impact of different hyperparameters on system performance, and how model performance is measured against industry standards (e.g., MAE, RMSE, MAPE). This will further strengthen both the theoretical and practical contributions of this study. Furthermore, the costs of integration and operational changes should be considered, with the future plan to integrate reinforcement learning algorithms for real-time price optimization.

REFERENCES

[1] Smith, J., & Lee, A. (2020). Retail Promotion Analytics: Methods and Applications. Journal of Retail Studies, 12(3), 45–67.
[2] Jones, P., & Wang, X. (2019). AI-based Pricing Models for Retail Optimization. International Journal of Data Science, 8(2), 101–115.
[3] Kumar, R., & Patel, S. (2021). ERP Integration in Retail Supply Chains. Enterprise Systems Journal, 15(1), 22–40.
[4] Lee, H., Chen, T., & Brown, M. (2022). Optimization Techniques in Retail Promotions. Operations Research Letters, 50(4), 310–320.
[5] Taylor, S. J., & Letham, B. (2018). Forecasting at Scale. The American Statistician, 72(1), 37–45.
[6] Shahriari, B., Swersky, K., Wang, Z., Adams, R. P., & de Freitas, N. (2016). Taking the Human Out of the Loop: A Review of Bayesian Optimization. Proceedings of the IEEE, 104(1), 148–175.
[7] Wager, S., & Athey, S. (2018). Estimation and Inference of Heterogeneous Treatment Effects Using Random Forests. Journal of the American Statistical Association, 113(523), 1228–1242.

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GREEN LEADERSHIP: AUTHENTIC SUSTAINABILITY OR GREENWASHING?

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Abstract: Nowadays, environmental protection is in greater focus, as consumers are more aware of the impact that industry has on it. For this reason, organizations are increasingly striving for sustainability. However, what the world is facing is misleading marketing, with which organizations only present themselves as environmentally responsible, but in fact they are not. This is greenwashing. In order for organizations to truly achieve authentic sustainability and avoid greenwashing, it is necessary to implement green leadership in the organization. A green leader must effectively lead and understand people, have developed a strong impact of environmental responsibility, and create success that meets both commercial and sustainability goals. This paper will present an overview of the literature related to the concept and dimensions of green leadership, explain the concept of greenwashing and its negative consequences, and present a comparison of authentic sustainability and greenwashing.
Key words: *green leadership, sustainability, greenwashing*

INTRODUCTION

In the last decade, sustainability has moved from the status of "wishful thinking" to a strategic necessity - markets are changing, regulations are tightening, and consumer and investor expectations are becoming more concrete. In this context, the question is no longer whether to deal with environmental protection, but how to do it in a way that simultaneously increases competitiveness, resilience and business sense. This is exactly where green leadership comes in as a modern approach to leadership that combines leadership skills with environmental literacy, systemic thinking and ethical responsibility [1]. Against this stands the appearance of greenwashing - a communication shortcut that promises "green" without changing the essence of the business model. It is most often recognized by general messages without metrics, highlighting minor improvements while leaving the main sources of impact intact, over-reliance on emissions offsets and selective data disclosure [2].
Sustainability is not a goal "next to" work; it is the way the business is planned, financed and executed. Green leadership thereby redefines the purpose of the organization - not only to generate profit, but also to leave a positive mark on the ecosystems in which it operates. Such a redefinition attracts talent looking for meaningful work, strengthens relationships with customers and partners, facilitates access to capital and increases resilience to changes brought about by climate, resource crises and new technologies [3].

GREEN LEADERSHIP

The concept of green leadership

Leadership is the ability to direct a team towards achieving common goals. The task of a leader is to motivate, inspire and lead people by example. Given that modern business is increasingly turning towards environmental protection, the need for leaders who "think green" is also emerging. Green leadership is a leadership style that strategically integrates environmental protection, climate responsibility and sustainable development into business processes and decisions, as well as into the relationship with stakeholders. The essence of green leadership is a clear vision and consistent implementation of sustainability expectations through all levels of the organization. Green leadership combines traditional leadership skills with a forward-looking proactive mindset. Competencies of a green leader include: systems thinking,

knowledge of regulations, environmental literacy, measurable initiatives. Ethical consistency and transparency are also necessary characteristics [1].

An important element of green leadership is organizational culture. In order for green leadership to work, the entire collective needs to be involved. Leaders are the ones who motivate and encourage their employees to "think and work green", by organizing trainings, motivating and rewarding employees. Green leaders inspire other employees by their example: from the way they use resources, making decisions to leading meetings. Such leaders empower experts from different functions to work together towards sustainability goals [1, 4]. Transparency and communication within the organization must be at a high level. Communication to the outside is equally important. Green leadership implies an honest dialogue with customers, regulators, investors and local communities. This includes the publication of accurate results concerning the area of environmental pollution, but also the involvement of interested parties, who can improve sustainable solutions with their proposals [5].
At the strategic level, the concept of green leadership means redefining the purpose of the organization: not only to generate profit, but also to positively influence the environment in which it operates. This attracts talented employees for quality and meaningful work, builds a positive reputation and attracts investors who value long-term sustainability. A business strategy built by green leadership implies: a clear climate strategy, an investment plan in energy efficiency, renewable energy sources and circular flows, as well as change management that ensures that people, processes and technologies move in that direction [6]. Therefore, green leadership is not only a campaign, but also a way of leadership that combines ethics, economics and ecology into a coherent whole of business decision-making.

Dimensions of green leadership

Increasing environmental pollution, climate change and growing market demands have made green leadership imperative in business. It implies that sustainability is understood as a source of innovation, efficiency and resilience of organizations. To do this systematically, it is useful to look at green leadership through four key dimensions, which include: strategy, operations, people and management. Each dimension brings its own practices and measurable indicators, and their integration ensures that sustainability does not remain a declarative goal, but becomes a way of leading, deciding and creating value for the organization [7, 8].
The first dimension refers to a clearly defined strategy and vision of sustainability. This strategy is fully included in the core business, in market decisions, innovation priorities and criteria for acquisitions. The green leader sets ambitious, but clear and realistic goals, such as switching to renewable energy sources, reducing resource consumption, recycling, introducing circular flows, etc. The key is to see sustainability as a generator of competitiveness: entry into new markets of low-carbon solutions, differentiation through eco-design, cost reduction through energy efficiency.
The second dimension is turning strategy into concrete operations and processes. Therefore, everything that was defined in the previous step through the strategy, is now put into practice. Installing solar panels to use the energy of the sun, as a renewable energy source, in product design, material minimization and substitution of critical raw materials, the ability to repair products and recycle parts, etc.
The third dimension is about people. Green leadership is sustainable only if it becomes part of the organizational culture: values, beliefs, habits, customs must be oriented towards environmental protection. Reward system, training, daily routines, informal rules must support sustainability. Leaders empower teams through targeted education (climate literacy, eco-design, circular models), setting the roles of "green champions" by function and mechanisms for collecting proposals from the "front line". The role of human resources management is to include sustainability competencies in job descriptions and development plans, and communication to constantly show progress and learn from failures without stigma.

The fourth dimension binds all previous ones through a solid system of management and measurement. A green leader introduces a clear ownership structure for sustainability goals: the board and executive team have defined responsibilities, and goals are linked to managers' bonuses and departmental budgets. Standardization of reporting and data quality control are key. Transparency means periodic, publicly available reports with clear progress, deviations and corrective measures.

THE TERM OF GREENWASHING

One of the characteristics of modern business is consumers, who have become more aware of the impact industry has on the environment and thereby influence its preservation. Good information, but also a critical attitude, as well as modern technologies, influence the fact that their voice is heard far away, but also influences changes. In response, organizations try to present themselves as environmentally responsible or sustainable, which is not always true. This leads to the concept of greenwashing. Greenwashing is a form of deceptive marketing, by which organizations try to present their practices as environmentally responsible or sustainable, while not actually implementing meaningful or genuine environmental initiatives. The essence of greenwashing is in communication manipulation manipulation: instead of investing effort in the actual reduction of emissions, waste or resource consumption, the focus is mainly on marketing, visual symbols and carefully chosen messages that should convince consumers, investors and regulators that the company is "green" [9, 10].
Greenwashing manifests itself through different patterns. Some of these forms relate to [11]:

- vague and general advertising - using terms such as "natural" product, without clear details and explanations;
- highlighting minor improvements as revolutionary - eg. the packaging has been changed, so the product is now "green", but the main problem has not actually been fixed;
- selective and incomplete publication of data - only positive indicators are shown, while key figures are kept silent;
- "hidden substitutes" - highlighting one green feature, while the entire product as a whole brings significant damage.

Motives for greenwashing are mainly commercial and reputational. Organizations want to meet the growing expectations of consumers and investors, stand out in the market and avoid reputational risks. Greenwashing creates the appearance of progress, without real costs and efforts [12].
Greenwashing has broader negative consequences for the market and society. It distorts fair competition, because organizations that invest in real changes may appear less "green" on paper than those that invest in marketing. Consumers are getting tired of and losing trust in environmental messages in general, making it difficult to change behavior and adopt sustainable solutions. Investors and banks can misjudge risks and opportunities, directing capital into projects that have no real impact on sustainability and environmental protection. At the level of public policy, greenwashing obscures the real picture of progress and can slow down the adoption and enforcement of effective regulations [13].
Greenwashing does not always have to be intentional; it often stems from the fragmentation of reporting systems, lack of capacity and short-term pressure on financial results. However, the consequences are the same: erosion of trust, regulatory and legal risks, missed opportunities for innovation and degradation of natural capital [12].

AUTHENTIC SUSTAINABILITY VS GREENWASHING

The difference between authentic sustainability and greenwashing is not only in the quality of marketing services, but also in the way of management, organizational architecture and financial discipline. Authentic sustainability relies on green leadership, which integrates environmental goals into strategy, processes, culture and management. In contrast,

greenwashing uses the language and aesthetics of sustainability to make business appear "greener" than it actually is [11, 14].
Authentic sustainability starts from materiality: identifying those impacts on the environment and society that are truly crucial for the company's activity and its stakeholders. In this context, Green leadership builds a clear path with goals by year, connected to budgets, investment decisions and the system of rewarding managers. Greenwashing avoids materiality and replaces it with general messages like "natural", "eco", "safe for the planet", without concrete evidence [15]. Operationally and technologically, authentic sustainability is measured by changes in "hard" metrics: energy and water audits, transition to renewable sources, replacement of high-emission technologies with low-carbon solutions, optimization of logistics and fuel, eco-design of products, and active waste management. Green leadership fosters pilot projects, tests hypotheses and scales what brings measurable benefits. In greenwashing, the focus is on "easy wins": green packaging without life cycle analysis, symbolic planting of trees that do not change the emissions profile [13, 16]. Communication is also very different. Authentic sustainability speaks to numbers, baselines and milestones. It states how the data was collected, what the assumptions are, where the results were achieved and where there are delays. Green leadership encourages honesty: publicly admits limitations and plans for corrective measures. Greenwashing avoids details, uses metaphors and images of nature, and selectively publishes data - eg. emphasizes the reduction of emissions in offices, while keeping silent about emissions from the supply chain or the product use phase [9, 10, 17]. In the relationship with customers and the community, authentic sustainability opens channels for feedback flows: repair, return, recycling programs, "product as a service" that extends life and reduces waste. Green leadership designs the user experience so that the sustainable option is easier and more profitable, not just "morally correct". Greenwashing focuses on aesthetics - green packaging, natural color palette - without changes in the function, durability and recoverability of the product [18].
Authentic sustainability is an operational, financial and cultural project that guides green leadership through: setting measurable goals, investing in technologies, integration through supply chains, transparent reporting and involving people. Greenwashing remains at the narrative level without changing the decision structure.

CONCLUSION

Authentic sustainability is a strategic and operational framework that embeds environmental goals into business decisions, processes and culture — not as a PR layer, but as a source of innovation, efficiency and long-term value. At the center is green leadership, which clearly defines the vision, sets a path with goals, directs sustainability capital. In contrast, greenwashing is a communication shortcut, which relies on highlighting general claims ("eco", "natural"), minor improvements and aesthetic changes without addressing the main sources of impact, often with an over-reliance on offsets and selective reporting. The risk to organizations is twofold: erosion of consumer and investor confidence, as well as regulatory and reputational costs when the gap between narrative and actual performance is exposed. That's why measurement, transparency and independent verification of data are a necessary condition of authenticity, not an "add-on" to communication.
In order to avoid greenwashing and ensure sustainable competitiveness, the organization should act through four dimensions of green leadership: sustainability strategy and vision, operations and processes, involving people in those processes and through stable management.
Interest in sustainability is growing in Serbia, but practice often stops at marketing messages, while essential impact measurement and transparent reporting are still in their infancy. As the country gradually aligns with European regulations, the difference between authentic sustainability and greenwashing is quickly becoming business critical. The solution in Serbia is to organize green leadership "end-to-end": from measurements and investments in clean energy and efficiency, through contractual requirements towards suppliers and clear financial

discipline, to transparent reporting and the active role of the state in setting the rules of the game and suppressing greenwashing.

REFERENCES

[1] Sultan, M., Hussain, S. Towards a sustainable workforce: integrating workplace spirituality, green leadership, and employee adaptability for green creativity. Discov Sustain Vol. 6, No.318, 2025. https://doi.org/10.1007/s43621-025-00971-x
[2] Feghali, K., Najem, R. Greenwashing in the era of sustainability: a systematic literature review. Corporate Governance and Sustainability Review / Vol. 9, Iss. 1, 2025.
[3] Magnusdottir, G. L., Widengård, M. Sweden's conflicting green leadership in the European Union. European Politics and Society, Vol.26, No,1, pp. 116–133. 2024. https://doi.org/10.1080/23745118.2024.2345689
[4] Kardoyo, K, Ferdy, M., Farliana, N., Nurkhin, A. Influence of the green leadership toward environmental policies support. The Journal of Asian Finance, Economics and Business,Vol. 7, No 11, 459-467, 2020
[5] Ahuja, J., Yadav, M., Sergio, R. P. Green leadership and pro-environmental behaviour: A moderated mediation model with rewards, self-efficacy, and training. Humanomics Vol. 39, pp. 481–501, 2023. doi: 10.1108/IJOES-02-2022-0041
[6] Orgun, E., Solunoglu, A., Kutlu, D., Kasalak, M. A., Unal, A., Celen, O., Gozen, E. The Effect of Green Leadership Perception on Environmental Commitment, Awareness, and Employees' Green Behavior in Hotel Businesses: Research from a Generation Cohort Theory Perspective. Sustainability, Vol. 16, No. 22, 9621. 2024. https://doi.org/10.3390/su16229621
[7] Amoako, G. K., Bonsu, G. A., Ampong, G. O. A., Gabrah, A Y. B., Sedalo, G. D., Conceptual framework: Green leadership enhances green customer citizenship behaviour. Sustainable Futures, Vol. 9, 100614, 2025. https://doi.org/10.1016/j.sftr.2025.100614
[8] Aycan, Z., Cinli, D., Robertson, J. L. Green leadership's predictors and outcomes. Nature Reviews Psychology Vol. 4, No. 3, 2025.
[9] Blame, C., Foerstl, K., Schleper, M. C. Antecedents of green supplier championing and greenwashing: An empirical study on leadership and ethical incentives. Journal of Cleaner Production, Vol. 152, pp. 339-350, 2017. https://doi.org/10.1016/j.jclepro.2017.03.052
[10] Abdullah, M., Wali Ullah, G. M., Turner, J. 50 shades of dark green: The nexus of narcissistic leadership and corporate greenwashing. International Review of Financial Analysis, Vol. 104, Pt. A, 104220, 2025. https://doi.org/10.1016/j.irfa.2025.104220
[11] Li, T., Shu, X., Liao, G. Does corporate greenwashing affect investors' decisions? Finance Research Letters, Vol. 67, Pt. A, 105877, 2024. https://doi.org/10.1016/j.frl.2024.105877
[12] Zhang X., Kong, L., Hu, X. Shades of green: The impact of greenwashing on stock price crash risk. Finance Research Letters, Vol. 70, 106285, 2024. https://doi.org/10.1016/j.frl.2024.106285
[13] Zioło, M., Bąk, I., Spoz, A. Literature review of greenwashing research: State of the art. Corporate Social Responsibility and Environmental Management, Vol. 31, No. 6, pp. 5343–5356, 2024. https://doi.org/10.1002/csr.2842
[14] Valero-Gil, J., Suárez-Perales, I., Ferrón-Vílchez, V. Would you date a liar? The impact of greenwashing on B2B relationships under the managerial trust view. BRQ Business Research Quarterly, Vol. 28, No. 3, pp. 731-749. 2024. https://doi.org/10.1177/23409444241250360
[15] Lengyel, A., Szőke, S. Kovács, S., Dávid, L. D., Bába, E. B., Müller; A. Assessing the essential pre-conditions of an authentic sustainability curriculum. International Journal of Sustainability in Higher Education, Vol. 20, No. 2, pp. 309–340. 2019. https://doi.org/10.1108/IJSHE-09-2018-0150

[16] Wark, C. Greenwashing vs Authentic Sustainability. GreenMach. https://www.greenmatch.co.uk/blog/greenwashing-vs-true-sustainability
[17] Hasan, K. Greenwashing vs. Authentic Sustainability: The Path to Responsible Branding. 2023. https://www.linkedin.com/pulse/greenwashing-vs-authentic-sustainability-path-branding-kumail-hasan
[18] Morrison, K., James A. 2009. "Authentic Sustainability: How the Reasons for Implementation Affect its Success." The International Journal of Environmental, Cultural, Economic, and Social Sustainability: Vol. 5, No. 1, pp. 107-114. doi:10.18848/1832-2077/CGP/v05i01/54561.

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THE IMPACT OF GREEN ORGANIZATIONAL CULTURE ON EMPLOYEE SATISFACTION IN SERBIA

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Abstract: This study examines the impact of green organizational culture on overall job satisfaction and its specific dimensions among employees in Serbia. Data were collected from 82 respondents across different industries and analyzed using regression techniques. The results show that green organizational culture has a significant and positive effect on job satisfaction, explaining 44.7% of its variance, with the strongest effects observed in communication, working conditions, and rewards. This study contributes to by providing an overview of the current state of green organizational culture and its relationship with job satisfaction in Serbia, highlighting that fostering a green organizational culture not only supports environmental sustainability but also increases employee well-being and workplace attitudes. Limitations of this study include the small sample size and the use of a shortened green organizational scale.
Key words: green organizational culture, job satisfaction, green, organizational culture

INTRODUCTION

Ecological sustainability has become an essential aspect of modern organizational development. Modern environmental problems, such as climate change, global warming, loss of biodiversity, air and water pollution, result from technological progress, population growth, and the irrational use of resources [1]. In response to these growing global challenges, organizations are increasingly focused on making sustainability an integral part of their core strategies in order to ensure long-term resilience and strengthen their competitive advantage [1, 2, 3, 4, 5]. One of the key approaches to achieving this objective is the incorporation of green practices into organizational culture, which enables firms to align sustainability with both ecological and operational objectives [1, 2].

There is a considerable amount of literature in this field, highlighting the importance of green organizational culture in the modern economy. According to [2], green organizational culture plays an important role in achieving sustainability, better organizational performance, and higher employee satisfaction. Some studies also point out that leadership behavior, when supported by a green-oriented culture, can have a positive effect on sustainable performance, with employee satisfaction and productivity acting as key links in that relationship [4, 6]. Still, motivating employees to behave in a more environmentally responsible way is often underdeveloped, even though such behavior can help strengthen the green culture and improve job satisfaction [1]. There are also attempts to conceptualize and measure green organizational culture, providing valuable insights into how deeply green values are integrated within organizations and how they influence both employee satisfaction and organizational performance [5].

Although research on environmental practices and aspects of green management exists in Serbia, the concept of green organizational culture and its impact on employees and organizational performance remains underexplored. Previous studies have mainly focused on the implementation of environmental standards, self-regulation [7], and HRM practices [8], while the way cultural values and norms influence employees' ecological behavior and its connection with job satisfaction has received much less attention.

In previous studies, the connection between green organizational culture and job satisfaction has often been examined through mediating or moderating variables. In the Serbian context, however, this relationship has not been sufficiently explored. This identified gap motivated the present study, which focuses on directly examining how green organizational culture influences job satisfaction in Serbia.

MATERIAL AND METHODS

Green organizational culture

Organizational culture represents a collective and long-lasting set of beliefs, norms, values, ideas, and attitudes that shape organizational behavior [2] and serve as a key driver of improved performance for both employees and managers [9]. It integrates employees, guides their decisions and behavior, and develops through collective learning as the organization navigates internal and external challenges [10]. Organizational culture, being socially constructed, multi-layered, and resistant to change [10], can be shaped by management to foster values that guide and support organizational objectives [2]. Authors in [2, 9, 10] explain that culture incorporates an organization's vision, values, norms, systems, symbols, language, assumptions, beliefs, and routines.

When these cultural elements are connected to environmental concerns, they create green organizational culture. This culture encourages employees to adopt common ecological values, focus on reducing environmental impact, and support long-term sustainability [11, 12]. Green organizational culture provides a framework that unites employees around shared ecological goals. It guides behavior, decision-making, and management processes toward environmentally friendly practices [2]. The concept of green organizational culture is still developing, and its definition is evolving [5, 13]. It represents collective ecological values and norms that guide employees' behavior and organizational practices. Authors in [5] emphasize that green organizational culture is a complex, multi-dimensional construct requiring a deeper cultural shift rather than superficial green initiatives.

Although many organizations adopt green policies, these actions are often superficial and insufficient for long-term sustainability [3, 13]. Real progress requires integrating sustainability into organizational culture. A green culture aligns employee values with environmental goals, influences everyday behavior, and turns strategies into measurable performance improvements [4, 6, 13]. Leaders and managers play a key role in creating and maintaining an environmentally friendly culture. When they demonstrate green values and behaviors, employees are encouraged to follow, which gradually transforms sustainability into part of the organizational culture [2, 13]. Transformational leadership is especially effective because it inspires deeper cultural change, motivates employees to act in line with environmental goals, and strengthens employees' awareness, commitment, and responsibility, ultimately leading to improved environmental performance [13].

Organizational culture plays a central role in shaping how employees perceive their workplace [10, 12, 14]. When cultural values and norms are aligned with employees' personal values, they foster stronger identification with the organization, which leads to higher job satisfaction [10, 12, 14, 15]. In this sense, green organizational culture can be viewed not only as a tool for ecological performance but also as a mechanism that supports employees' motivation, commitment, and satisfaction [2, 4, 6]. Since the focus of this paper is on the influence of green organizational culture on job satisfaction, it is necessary to clarify the concept of job satisfaction and understand its key determinants.

Job satisfaction

Job satisfaction is an employee's emotional experience, whether pleasant or unpleasant, that arises from the evaluation of their work and workplace environment [14]. It depends on opportunities for advancement, reward systems, relationships with management, job security, and conditions that enable active employee engagement [15]. Job satisfaction is closely linked with key organizational outcomes, since satisfied employees are more productive, motivated, and engaged, which contributes to organizational success, reduces absenteeism, and lowers turnover costs [16, 17]. It can also foster motivation, commitment, initiative, and involvement in innovative practices [2, 4, 6, 15]. Spector [18] explains job satisfaction in two ways:

- as a general feeling toward the job, representing the overall emotional state of employees about their work, and

- as satisfaction with specific aspects of the job, such as pay, promotion opportunities, working conditions, or relationships with colleagues and supervisors.

From the first perspective, job satisfaction is seen as a global attitude toward work, while from the second, it may vary across different dimensions. Employees can therefore be satisfied with some aspects of their job, but not necessarily with all.
Spector [18] developed the Job Satisfaction Survey (JSS), which measures nine dimensions: pay, promotion opportunities, benefits, supervisors, coworkers, rewards, the nature of work, communication, and operating procedures. Research shows a positive link between working conditions, job structure, and job satisfaction. Fair pay and benefits, such as health insurance, pensions, and flexible hours, improve satisfaction [19, 20]. Promotion opportunities and professional growth also play a key role, while their absence may lead to dissatisfaction [21]. Clear procedures reduce stress and help employees work more effectively. The nature of work is important too because employees who see their job as meaningful are more engaged and committed [20]. When organizations integrate environmental or green initiatives into their operations, employees often perceive their work as more purposeful [2, 6]. Social support from colleagues and supervisors, constructive feedback, and open communication build trust and strengthen identification with the organization, all of which increase job satisfaction [21]. This shows that job satisfaction is a multidimensional construct, not only a general attitude toward work. This approach helps to better explain outcomes like organizational commitment, job performance, and turnover intention [19, 21].

Green organizational culture and job satisfaction

Previous research [6, 9, 10, 19] has shown a strong connection between organizational culture and job satisfaction, because organizational culture shapes the work environment, relationships, and overall employee experience.
In this context, green organizational culture adds a unique dimension, as it not only supports ecological sustainability but also improves employee well-being [1, 2, 4, 6, 11, 12]. A green culture promotes healthier and safer working conditions, reduces environmental risks, and fosters collective responsibility, all of which can contribute to higher satisfaction at work [4, 6]. Furthermore, organizations that integrate green values into their reward systems, training, and teamwork create conditions where employees feel motivated, valued, and more engaged in their roles [6, 21]. Training and development related to environmental practices increase competencies and create a sense of purpose [12, 22], while recognition of pro-environmental behavior reinforces commitment and satisfaction. When employees identify with the ecological values of their organization, they often experience greater pride, loyalty, and emotional attachment, which further increases their job satisfaction [6, 12].
Based on previous research findings and theoretical background, the following hypotheses were formulated:
H1. Green organizational culture (GOC) has a positive effect on job satisfaction (JS).
H2. Green organizational culture (GOC) has a positive effect on all dimensions of job satisfaction: pay (P), promotion opportunities (PO), fringe benefits (B), supervisors (S), coworkers (C), contingent rewards (CR), the nature of work (W), communication (CM), and operating procedures (OP).

Methodology

The main objective of this study was to examine how green organizational culture impacts job satisfaction in Serbia. For the purposes of the research, an adapted questionnaire was developed, consisting of 49 questions divided into three main sections. All sections were adapted from previous studies to ensure reliability and relevance.
The first part included general questions about the participants. The second part used one of the most commonly applied instruments for measuring job satisfaction known as Spector's Job Satisfaction Survey [18]. It contained 36 items, with each dimension of job satisfaction (JS)

assessed through four statements. The third part referred to green organizational culture (GOC) and included six items, adapted from [6]. All items were rated on a six-point Likert scale, ranging from "absolutely disagree" to "absolutely agree."

Out of 87 participants, 82 valid responses were collected during the data collection period in September 2025. The data were analyzed using SPSS software. Preliminary analyses included descriptive statistics to summarize sample characteristics, reliability testing with Cronbach's alpha to assess internal consistency, and regression analysis to explore relationships between variables.

The respondents were employees from various organizations in the Republic of Serbia, representing different hierarchical levels and educational backgrounds. Women made up the majority of the sample (65.4%), while men accounted for 34%. Participants' ages ranged from 20 to 60 years, with the largest group being 20–30 years old (50.6%). The least represented were those aged 51–60 (4.9%).

Regarding education, most participants (34.6%) held a university degree, followed by those with a high school diploma (29.6%). There were no participants with only primary education or a doctoral degree, which somewhat limits insights into the effects of the lowest and highest levels of education on the variables analyzed.

In terms of work experience, the largest share of participants (43.2%) had five years or less, indicating a relatively younger population with shorter professional experience. Additionally, 25% held managerial positions. Most respondents were employed in micro and small enterprises (61.7%), while about 30% worked in large companies.

RESULTS AND DISCUSSION

Reliability analysis was performed for all variables using Cronbach's alpha coefficient. The results, presented in Table 1, show that all eleven scales demonstrated satisfactory internal consistency. Table 1 also presents descriptive statistics for all variables, including the number of items, means, standard deviations, skewness, and kurtosis values.

Table 1. *Results of reliability and descriptive analysis and normality tests*

Variable	Cronbach's α	Num	Mean	St. Dev.	Skewness	Kurtosis
P	0.822	4	3.4024	1.41299	-0.047	-1.039
PO	0.880	4	3.5305	1.63271	-0.084	-1.053
B	0.921	4	3.6372	1.43917	-1.053	-0.892
S	0.734	4	4.3689	1.37898	-0.196	-1.130
C	0.727	4	3.6921	1.52160	-0.138	-1.152
CR	0.826	4	3.6738	1.47022	-0.173	-0.864
W	0.839	4	3.8872	1.11745	-0.329	-0.776
CM	0.841	4	4.2104	1.18209	-0.518	-0.622
OP	0.704	4	4.3445	1.15312	-0.224	-0.730
JS	0.964	9	3.9258	1.16075	-0.264.	-0.739
GOC	0.950	6	4.1159	1.11263	0.77	-1.212

The reliability of all scales was satisfactory, with Cronbach's α values above 0.70 [24]. The highest internal consistency was found for JS (M_{JS}=0.964) and GOC (M_{GOC}=0.950), while CM and OP had slightly lower but still acceptable values. On average, respondents reported moderate to high levels of job satisfaction. The lowest ratings were given to P and PO (3.40 and 3.53), while S and OP received the highest scores. JS was rated moderately high, and GOC was also positively evaluated, although with somewhat greater variability.

Most of the skewness and kurtosis values were slightly negative. Negative skewness values indicate that a greater number of values are clustered on the higher side of the distribution. Negative kurtosis values suggest that the distributions are slightly flatter than a normal distribution, implying lighter tails and a broader peak [24]. The exception was GOC, where

positive skewness suggested more dispersed and lower responses. Normality of data distribution was tested using the Kolmogorov–Smirnov test. Results showed that most variables deviated from normal distribution ($p < 0.05$), while only three dimensions (P, PO, and C) did not significantly deviate ($p > 0.05$). The Kolmogorov–Smirnov test indicated that most variables did not follow a normal distribution ($p < 0.05$). However, since the values of skewness and kurtosis do not significantly deviate from the range commonly considered acceptable for normality (±2 for social sciences), it can be concluded that the assumption of normality has been reasonably met [24]. The absence of extreme values and the Durbin-Watson statistics (from 2.068 to 1.816) suggest that autocorrelation in models does not interfere with the implementation of regression analysis. The results of regression analysis are presented in Table 2.

Table 2. *Linear regression analysis*

Dependent variable: JS, r = 0.668, R^2 = 0.447, Adjusted R^2 = 0.440, F (1, 80) = 64.61, p < 0.001					
Variable	B	Standard Error	Beta	t	Sign. (p)
Constant	2.248	0.230	-	9,797	0.000
GOC	0.475	0.059	0.668	8.038	0.000
Dependent variable: P, r = 0.592, R^2 = 0.350, Adjusted R^2 = 0.342 F (1, 80) = 43.08, p < 0.001					
Variable	B	Standard Error	Beta	t	Sign. (p)
Constant	1.595	0.303	-	5.262	0.000
GOC	0.512	0.078	0.592	6.564	0.000
Dependent variable: PO, r = 0.580, R^2 = 0.336, Adjusted R^2 = 0.328 F (1, 80) = 40.50, p < 0.001					
Variable	B	Standard Error	Beta	t	Sign. (p)
Constant	1.833	0.312	-	5.875	0.000
GOC	0.511	0.080	0.580	6.364	0.000
Dependent variable: B, r = 0.566, R^2 = 0.321, Adjusted R^2 = 0.312 F (1, 80) = 37.76, p < 0.001					
Variable	B	Standard Error	Beta	t	Sign. (p)
Constant	2.680	0.302	-	8.863	0.000
GOC	0.478	0.078	0.566	6.145	0.000
Dependent variable: S, r = 0.569, R^2 = 0.355, Adjusted R^2 = 0.347 F (1, 80) = 44.03, p < 0.001					
Variable	B	Standard Error	Beta	t	Sign. (p)
Constant	1.732	0.325	-	5.326	0.000
GOC	0.555	0.084	0.596	6.635	0.000
Dependent variable: C, r = 0.588, R^2 = 0.346, Adjusted R^2 = 0.337 F (1, 80) = 42.26, p < 0.001					
Variable	B	Standard Error	Beta	t	Sign. (p)
Constant	1.805	0.316	-	5.703	0.000
GOC	0.529	0.081	0.588	6.501	0.000
Dependent variable: CR, r = 0.610, R^2 = 0.372, Adjusted R^2 = 0.364 F (1, 80) = 47.43, p < 0.001					
Variable	B	Standard Error	Beta	t	Sign. (p)
Constant	2.413	0.236	-	10.243	0.000

GOC	0.418	0.061	0.610	6.887	0.000
Dependent variable: W, r = 0.628, R^2 = 0.395, Adjusted R^2 = 0.387 F (1, 80) = 44.68, p < 0.001					
Variable	B	Standard Error	Beta	t	Sign. (p)
Constant	2.604	0.245	-	10.644	0.000
GOC	0.455	0.063	0.628	7.224	0.000
Dependent variable: CM, r = 0.649, R^2 = 0.421, Adjusted R^2 = 0.414 F (1, 80) = 45.35, p < 0.001					
Variable	B	Standard Error	Beta	t	Sign. (p)
Constant	2.727	0.233	-	11.679	0.000
GOC	0.458	0.060	0.649	7.627	0.000
Dependent variable: OP, r = 0.529, R^2 = 0.279, Adjusted R^2 = 0.270 F (1, 80) = 31.01, p < 0.001					
Variable	B	Standard Error	Beta	t	Sign. (p)
Constant	2.844	0.251	-	11.318	0.000
GOC	0.360	0.065	0.529	5.569	0.000

The findings of this study demonstrated that GOC has a significant and positive effect on JS, explaining 44.7% of its variance (R^2 = 0.447). In addition to the global effect, GOC was also found to be a significant predictor of all specific dimensions of JS, with explained variance ranging from 27.9% (OP) to 42.1% (C). The strongest effects were observed for C (R^2 = 0.421, β = 0.649), W (R^2 = 0.395, β = 0.628), and CR (R^2 = 0.372, β = 0.610), suggesting that GOC plays a particularly important role in shaping interpersonal relationships, the quality of the work environment, and employees' perceptions of being valued. These results confirm both H1 and H2.

The results of this study are consistent with previous research [6, 12] that highlighted the positive role of GOC in shaping employee attitudes. Similar to [6], which found that GOC significantly increases both JS and organizational commitment, the present findings confirm that GOC has a strong positive impact on JS, as well as on all its individual dimensions. While [6] emphasized the mediating role of JS in linking GOC and organizational commitment, this study adds further evidence by showing that GOC directly contributes to multiple aspects of JS, such as communication, recognition, and working conditions. In both cases, the results suggest that fostering a GOC benefits not only environmental sustainability but also employee well-being.

CONCLUSION

The conducted research aimed to examine whether green organizational culture influences overall job satisfaction and its specific dimensions in Serbia. Our findings suggest a strong and positive relationship between green organizational culture and job satisfaction, indicating that employees who perceive their organizations as environmentally responsible also report higher satisfaction with their work. These findings strengthen the argument that organizations should invest in cultivating a green culture, as it improves employees' job satisfaction at both the global and dimensional level. The results show that the biggest positive impacts are seen in coworker relations, working conditions, and recognition, pointing managers toward the areas where green culture can most effectively improve both sustainability and employee satisfaction.

Although the present study offers useful insights into how green organizational culture relates to job satisfaction in Serbia, it also has a few notable limitations. The main limitation is the relatively small sample (N = 82), which restricts the generalizability of the findings. Moreover, while previous research suggests that job satisfaction may vary depending on factors such as industry [4, 6], company size, gender [23], and job position, these potential differences could

not be examined here due to the limited sample, as such analyses would not have yielded reliable results. Second, this study relied on a shortened version of the questionnaire measuring green organizational culture, which did not capture the full range of its specific dimensions, (more in [5]), thereby limiting the depth of the analysis.
Future research should address these limitations by including larger and more diverse samples that would allow for subgroup comparisons, as well as by employing more comprehensive instruments to measure the multidimensional nature of green organizational culture. In doing so, future studies could provide a more nuanced understanding of how green organizational culture operates across different organizational contexts and employee characteristics, thereby strengthening the validity and applicability of the findings.

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REFERENCES

[1] Tsymbaliuk, S., Vasylyk, A., & Stoliaruk, K. Staff motivation for green behaviour and environmental initiatives. The Eurasia Proceedings of Educational and Social Sciences, Vol.24, pp 78-83. 2022. DOI:10.55549/epess.1179692
[2] Adiguzel, Z., & Sonmez Cakir, F. Empowering sustainability: green entrepreneurial orientation, innovative strategies, culture and operational performance. Management Decision. 2025. DOI:10.1108/MD-07-2024-1700
[3] De Giacomo, M. R., & Bleischwitz, R. Business models for environmental sustainability: Contemporary shortcomings and some perspectives. Business Strategy and the Environment, Vol.29, No.8, pp 3352-3369, 2020. DOI:10.1002/bse.2576
[4] Altassan, M. A. How the Leadership Style Influences the Firm's Sustainable Performance by Boosting Employee Satisfaction and Productivity: The Role of Green Organizational Culture. Pakistan Journal of Life & Social Sciences, Vol.22 No.1, pp. 1198-1219. 2024. DOI:10.57239/PJLSS-2024-22.1.0082
[5] Aggarwal, P., & Agarwala, T. Green organizational culture: An exploration of dimensions. Global Business Review, Vol.26, No.4, pp 1103-1126. 2025. DOI:10.1177/09721509211049890
[6] Shahriari, M., Tajmir Riahi, M., Azizan, O., & Rasti-Barzoki, M. The effect of green organizational culture on organizational commitment: The mediating role of job satisfaction. Journal of Human Behavior in the Social Environment, Vol.33, No.2, pp 180-197. 2022. DOI: 10.1080/10911359.2022.2029789
[7] Mijatovic, I., Maricic, M., & Horvat, A. The factors affecting the environmental practices of companies: The case of Serbia. Sustainability, Vol.11, No.21, 5960. 2019. DOI:10.3390/su11215960
[8] Jaganjac, J., Nikolić, J. L., & Lazarević, S. The importance of green human resource management practices for sustainable organizational development: Evidence from Serbia and Bosnia and Herzegovina. JEEMS Journal of East European Management Studies, Vol.29, No.1, pp 157-180. 2024. DOI: 10.5771/0949-6181-2024-1-157
[9] Iskamto, D. Organizational culture and its impact on employee performance. International Journal of Management and Digital Business, Vol.2, No.1, pp 47-55. 2023. DOI:10.54099/ijmdb.v2i1.584
[10] Akpa, V. O., Asikhia, O. U., & Nneji, N. E. Organizational culture and organizational performance: A review of literature. International journal of advances in engineering and management, Vol.3, No.1, pp 361-372. 2021. DOI:10.35629/5252-0301361372
[11] Tahir, R., Athar, M. R., Faisal, F., Shahani, N. U., & Solangi, B. Green organizational culture: A review of literature and future research agenda. Annals of Contemporary

Developments in Management & HR (ACDMHR), Vol.1, No.1, pp 23-38. 2019. DOI:10.33166/ACDMHR.2019.01.004
[12] Maryatmi, A. S. Job satisfaction as a mediator of career development and job security for well-being. International Journal of Innovation, Creativity and Change., Vol.12, No.3, pp 271-282. 2020.
[13] Rizvi, Y. S., & Garg, R. The simultaneous effect of green ability-motivation-opportunity and transformational leadership in environment management: the mediating role of green culture. Benchmarking: An International Journal, Vol.28, No.3, pp 830-856. 2021. DOI:10.1108/BIJ-08-2020-0400
[14] Saleh, R., & Atan, T. The involvement of sustainable talent management practices on employee's job satisfaction: Mediating effect of organizational culture. Sustainability, Vol.13, No.23, 13320. 2021. DOI: 10.3390/su132313320
[15] Men, L. R., & Robinson, K. L. It's about how employees feel! examining the impact of emotional culture on employee–organization relationships. Corporate Communications: An International Journal, Vol.23, No.4, pp 470-491. 2018. DOI:10.1108/CCIJ-05-2018-0065
[16] Bogićević Milikić B.& Čučković, M. How To Increase Job Satisfaction And Organisational Commitment In The Ict Sector Through Job Design, Economic Annals, Vol.64 No.222, pp 81-116. 2019. doi:10.2298/EKA1922081B
[17] Bowling, N. A., Wagner, S. H., & Beehr, T. A. The Facet Satisfaction Scale: An effective affective measure of job satisfaction facets. Journal of Business and Psychology, Vol.33, No.3, pp 383–403. 2018. DOI:10.1007/s10869-017-9499-4
[18] Spector, P. Measurement of Human Service Staff Satisfaction: Development of the Job Satisfaction Survey. American Journal of Community Psychology, Vol.13, No.6, pp 693-713. 1985.
[19] Janićijević, N., Kovačević, P., & Petrović, I. Identifying organizational factors of job satisfaction: The case of one Serbian company. Economic Annals, Vol.60, No.205, pp 73–104. 2015. DOI:10.2298/EKA1505073J
[20] Kaplan, S. A., Winslow, C. J., & Luchman, J. N. What are we working for? Comparing the importance of job features for job satisfaction over the career span. Social Indicators Research, Vol.148, No.3, pp 1021–1037. 2020. DOI:10.1007/s11205-019-02231-8
[21] Yalabik, Z.Y., Rayton, B.A. and Rapti, A. Facets of job satisfaction and work engagement, Evidence-based HRM, Vol.5, No.3, pp 248-265. 2017. DOI:10.1108/EBHRM-08-2015-0036
[22] Ersoy, A. The relationship between job satisfaction and turnover intention: A metaanalysis, Journal of Human and Work, Vol.11 No.2, pp 115–124. 2024. DOI:10.18394/iid.
[23] Chaudhary, R. Green human resource management and employee green behavior: an empirical analysis. Corporate Social Responsibility and Environmental Management, Vol.27, No.2, pp 630-641. 2020. DOI:10.1002/csr.1827
[24] Pallant, J. (2011). SPSS: Priručnik za preživljavanje: postupni vodič kroz analizu podataka pomoću SPSS-a. Prevod 4. izdanja, Beograd: Mikroknjiga

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THE FOUNDATION OF GREEN MINING – PRINCIPLES AND SUSTAINABILITY

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Abstract: This paper provides a theoretical overview of the definitions and principles of green mining, historical development and essential information. In particular, the pillars of sustainability of green mining are analyzed from an environmental, social and economic perspective. A selection of relevant international and national regulatory frameworks and industry initiatives that play a key role in shaping green mining is made.
Key words: green mining, environmental sustainability, social responsibility

INTRODUCTION

Mining, as one of the oldest human activities, has always been crucial for the advancement of civilization. However, the long history of industrial exploitation has often left a deep ecological footprint and caused social tensions. The concept of Green Mining represents a radical shift in this approach, offering a vision of an industry that not only provides essential raw materials but does so in a way that actively contributes to environmental preservation, improving the quality of life for local communities, and long-term economic sustainability. This paper lays the theoretical and philosophical groundwork for understanding this transformative paradigm, defining its key principles and positioning it within the broader global context of sustainable development. By analyzing the environmental, social, and economic pillars of sustainability, and by reviewing current global trends and regulations, this paper aim to provide a comprehensive framework for applying green principles at all stages of the mining cycle.

DEFINITION AND EVOLUTION OF GREEN MINING

Green Mining is an integrated approach to the extraction of mineral resources that aims to minimize negative impacts on the environment and society, while maximizing economic efficiency and sustainability [1]. It differs from traditional practices by its proactive and holistic approach, striving for mining operations to become part of the solution rather than a source of problems. Green Mining entails minimizing the footprint: Reducing the surface footprint of a mine, decreasing the amount of waste rock and tailings. It uses resources efficiently: optimizes the consumption of energy, water and other resources through innovative technologies and processes. Emission reduction occurs in Green Mining. Emissions of greenhouse gases, dust, and pollutants into water and air are controlled and reduced [2]. To protect biodiversity, there are planning and implementation measures to preserve local ecosystems and biodiversity [3]. Green mining reclamation is the crucial process of restoring land to a stable, beneficial state after mining operations cease, ensuring it's safe for future use. Reclamation and closure are mandatory after the completion of extraction [4]. Social responsibility of green mining is essential. Active involvement of local communities, respect for human rights and ensuring safe working conditions are the test of success [5, 6].

Historical perspective and evolution

For centuries, traditional mining has focused on maximum extraction with minimal consideration of environmental and social consequences. It has often resulted in massive landscape destruction, water and air pollution, and social conflict. The reactive approach (late 20th century) is reflected in the introduction of regulations in response to environmental disasters and growing public awareness. The focus is on "cleaning up" existing pollution and setting baseline standards. The proactive approach (early 21st century) developed from the understanding that prevention is better than cure. Technologies and methodologies are being developed to reduce the impact of pollution from the very beginning of a project. The integrated and holistic approach (modern green mining) is the concept that mining must be fully integrated into the natural and social ecosystem, aiming for a positive net impact. This includes the circular economy - where waste from one process becomes a resource for another, reducing the need for new raw materials and minimizing waste disposal in landfills [2].

Scientific Justification – Why Green Mining Is an Imperative?

The need for green mining is not just an ethical issue; it is deeply rooted in scientific evidence on the harmful effects of traditional mining practices and the urgency of addressing global environmental and social challenges. For climate change and decarbonization, the mining industry is a significant emitter [7]: Traditional mining is a major consumer of energy, predominantly from fossil fuels, and a significant contributor to greenhouse gas (GHG) emissions. Studies show that mining and metal processing account for approximately 4-7% of global GHG emissions [8]. The transition to renewable energy sources, the electrification of the fleet and the optimization of processes in green mining directly reduce this impact, which is key to achieving the goals of the Paris Agreement [9]. On the other hand, the development of green technologies (electric vehicles, solar panels, wind turbines) requires an exponential increase in the production of metals such as lithium, cobalt, copper, nickel and rare earth elements. The scientific community announces that this increased demand must not negate the environmental benefits of these technologies. Green mining ensures that these metals are produced in a sustainable way, minimizing their impact on the life cycle [10].

Ecosystem devastation and biodiversity loss occur due to habitat fragmentation and pollution. Open pit mines, tailings dumps and road networks fragment natural habitats, while wastewater and dust discharges directly threaten plant and animal species. Research shows that mining is one of the main drivers of biodiversity loss in certain regions [11]. Green mining, with a focus on footprint reduction and reclamation, is scientifically supported as a method to mitigate these effects and support ecological restoration. A particular problem is acid mine drainage (AMD), which is formed by the oxidation of sulfide minerals in the presence of water and air. It is one of the most serious and long-lasting environmental problems of traditional mining. AMD lowers the pH of water and releases heavy metals, resulting in lethal conditions for aquatic life and contamination of food chains. Scientific research has developed techniques for passive and active treatment of AMD, as well as methods for preventing its formation (e.g., covering sulfide materials), which are an integral part of green mining [12].

Water scarcity and pollution of water resources are widespread. Mining, especially ore processing, is extremely water-intensive. In water-scarce regions, this creates significant conflicts with local communities and agriculture. UN and World Bank studies indicate that by 2030, global water demand could increase by 40%, forcing the mining industry to drastically reduce consumption and improve water recycling [13]. Another water-related problem is heavy metal pollution. The uncontrolled discharge of mine wastewater, which often contains heavy metals (mercury, arsenic, lead, cadmium), cyanides and sulfates, has catastrophic consequences for human health and ecosystems. Numerous scientific studies document the bioaccumulation of these toxins in the food chain, with long-term health consequences.

Green mining, through advanced treatment systems and closed-loop water systems, offers scientifically validated solutions to prevent this pollution [14].
There is a proven correlation between the proximity of mines and increased incidence of respiratory diseases, skin diseases and birth defects in local communities due to dust and toxic pollution (WHO reports). Studies in sociology and development economics show that traditional mining projects, without adequate community engagement and fair sharing of benefits, often lead to social tensions, migration and deterioration of the socio-economic status of the local population. Green mining, with its emphasis on social responsibility and participation, is a scientifically based approach to building positive relationships and improving living conditions [2].
There is also the issue of limited resources and the need for a circular economy. Scientific models of resource consumption clearly show that mineral resources are finite. The extraction rate of many key metals significantly exceeds their natural renewal rate. The concept of a circular economy, which is central to green mining, is scientifically supported as a way to extend the life of resources through recycling, reuse and waste reduction. Scientific approaches are being developed for "urban mining" – the extraction of metals from electronic waste and other discarded products [15]. Although not traditional mining, it is an integral part of the broader concept of green mining because it reduces pressure on primary sources and is an important aspect of the circular economy.

THE PILLARS OF SUSTAINABILITY IN GREEN MINING

Sustainability in mining rests on three interdependent pillars: environmental, social, and economic. None of these pillars can function independently without the support of the others.

Environmental Sustainability

Environmental sustainability in mining refers to minimizing the negative impact of mining operations on the natural environment and actively contributing to its restoration and conservation. This includes conducting detailed studies of flora and fauna before mining activities begin to identify sensitive species and habitats, as well as designing mines that minimize impacts on critical habitats. Sometimes, it is necessary to relocate endangered species and reintroduce them to protected areas.
Water management is crucial [2], such as:

- Implementing technologies that reduce the need for fresh water (e.g. dry milling, recycling process water).
- Treating mine water to standards for reuse or safe discharge into natural waterways. Removing heavy metals and sulfates.
- Protecting groundwater aquifers from contamination and monitoring groundwater levels.
- Managing stormwater to capture and divert precipitation to prevent runoff of pollutants.

Air and emissions management, as well as waste management (tailings and waste rock), are also important in Green Mining. Dust control possible through the use of water spray systems, enclosed conveyor belts and efficient exhaust filters [16]. In particular, tailings stabilization systems are being developed to prevent pollutant leakage and erosion [17]. Ultimately, the circle closes with land reinstatement and reclamation in parallel with mining operations, rather than waiting for the end of extraction.

Social Responsibility

Social responsibility in mining encompasses the obligation of mining companies to make a positive contribution to society, respect human rights and build trust with local communities.

This includes involving local communities in the project planning process from the earliest stages, openly communicating about the impacts, benefits and risks of mining operations, and establishing clear and accessible channels for expressing concerns and resolving conflicts. It is possible and desirable to form partnerships with local authorities, non-governmental organisations and the community to implement development projects. In the internet era, safety and health education for both green mining workers and the rest of the population around the mine, including children, is desirable. The availability of data on the methods of exploitation in a "green" mine enables peace and economic stability. For artisanal and small-scale mining, green mining would save many lives [18].

Economic Viability

Economic viability in the context of green mining goes beyond short-term profit, focusing on long-term financial sustainability taking into account environmental and social factors. Operating costs are reduced due to energy efficiency, water and waste recycling. Compliance with environmental and social standards reduces the risk of fines, lawsuits and work stoppages. Investors increasingly prefer green projects, which facilitates access to financing on more favorable terms. Due to the positive reputation of the mine, the value of the company increases [2]. This has enabled the formation of new business models of the circular economy (recycling and reuse of materials, extraction of valuable metals from waste and tailings, restoration of biodiversity).

GLOBAL TRENDS AND REGULATORY FRAMEWORKS

International and national regulatory frameworks, as well as industry initiatives, play a key role in shaping green mining. The following can be highlighted:

1. Initiative for Responsible Mining (IRMA) - a standard that covers a wide range of environmental and social issues, allowing for a transparent assessment of mining operations.
2. Towards Sustainable Mining (TSM) - A Canadian program that helps mining companies manage key environmental and social risks.
3. Principles for Responsible Investment (PRI) - A framework for investors to incorporate ESG factors into their decisions.
4. ISO standards: ISO 14001 (environmental management) and ISO 45001 (occupational health and safety) as key certifications.

National laws and regulations should be aligned with green mining principles. This should particularly apply to exploration and exploitation permit processes. Voluntary certification to international standards is evidence of commitment to green mining. Sustainability reporting: and the role of third parties are inextricably linked to the public data and the internet. This is why education on green mining is very important.

CONCLUSION

This paper has laid a solid foundation for understanding Green Mining as an integral and indispensable component of sustainable development. By adding scientific justification, we have clearly shown that the transition to green mining practices is not only an ethical imperative but also a scientifically grounded response to global challenges such as climate change, biodiversity loss, water scarcity, and social inequality. We have emphasized that the transformation of the mining sector is not just about technical innovations but also about a profound change in mindset and business practices. Embracing the environmental, social, and economic pillars of sustainability, along with aligning with global trends and regulatory frameworks, is crucial for creating a mining industry that is responsible, profitable, and

accepted by society. Thispaper serves as a basic platform from which we will build further, exploring specific techniques, models, and future visions in the subsequent papers.

REFERENCES

[1] Xiao, Y., Deng, H., Wang, P., & Xu, J. (2025). Exploring green mining research trends through web of science: A bibliometric analysis based on VOSviewer and CiteSpace. Sustainable Environment, 11(1). https://doi.org/10.1080/27658511.2025.2505288

[2] Onifade M., Zvarivadza T., Adebisi A. J., Said O. K., Dayo-Olupona O., Lawal I. A., Khandelwal M., Advancing toward sustainability: The emergence of green mining technologies and practices, Green and Smart Mining Engineering, Volume 1, Issue 2, 2024, Pages 157-174, ISSN 2950-5550, https://doi.org/10.1016/j.gsme.2024.05.005. https://www.sciencedirect.com/science/article/pii/S2950555024000338

[3] Worlanyo A.S., Jiangfeng L., Evaluating the environmental and economic impact of mining for post-mined land restoration and land-use: a review, Journal of Environmental Management. Volume 279, 2021, 111623, ISSN 0301-4797, https://doi.org/10.1016/j.jenvman.2020.111623. https://www.sciencedirect.com/science/article/pii/S0301479720315486

[4] Zine H., Mansour E. A., Hakkou R., Papazoglou G. E., Benzaazoua M., Advancements in Mine Closure and Ecological Reclamation: A Comprehensive Bibliometric Overview (1980-2023), Mining 2023, 3(4), 798-813; https://doi.org/10.3390/mining3040044

[5] Pons A., Vintrò C., Rius J., Vilaplana J., Impact of Corporate Social Responsibility in mining industries, Resources Policy, Volume 72, 2021, 102117, ISSN 0301-4207, https://doi.org/10.1016/j.resourpol.2021.102117. https://www.sciencedirect.com/science/article/pii/S0301420721001318

[6] Jianchun Y., Effects of green mining practices on corporate sustainable development: role of green innovation, green organizational commitment, and corporate social responsibility, Frontiers in Environmental Science, 11 December 2024, Sec. Environmental Economics and Management, Volume 12 – 2024, https://doi.org/10.3389/fenvs.2024.1476075

[7] Dorrell A., Decarbonising the mining industry, Australian Mining Review, September 6, 2024, https://australianminingreview.com.au/features/decarbonising-the-mining-industry/

[8] Enemuo M., Ogunmodimu O., Transitioning the mining sector: A review of renewable energy integration and carbon footprint reduction strategies, Applied Energy, Volume 384, 2025, 125484, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2025.125484. https://www.sciencedirect.com/science/article/pii/S0306261925002144

[9] The Paris Agreement, United Nations, 2015., https://www.un.org/en/climatechange/paris-agreement

[10] The Role of Critical Minerals in Clean Energy Transitions, World Energy Outlook Special Report, 2021., https://iea.blob.core.windows.net/assets/278ae0c8-28b8-402b-b9ab-6e45463c273f/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf

[11] Sonter LJ, Ali SH, Watson, JEM. 2018 Mining and biodiversity: key issues and research needs in conservation science., Proc. R. Soc. B 285: 20181926., http://dx.doi.org/10.1098/rspb.2018.1926

[12] Park I., Baltazar Tabelin C., Jeon S., Li X., Seno K., Ito M., Hiroyoshi N., A review of recent strategies for acid mine drainage prevention and mine tailings recycling, Chemosphere, Volume 219, 2019, Pages 588-606, ISSN 0045-6535, https://doi.org/10.1016/j.chemosphere.2018.11.053. https://www.sciencedirect.com/science/article/pii/S0045653518321568

[13] WATER RESOURCES MANAGEMENT, World Bank , Oct 05, 2022, https://www.worldbank.org/en/topic/waterresourcesmanagement
[14] Chernyshova V. I., Suup M., Kihlblom C., Rao Kota H., Ponnurangam S., Green mining of mining water using surface e-precipitation, Separation and Purification Technology, Volume 327, 2023, 125001, ISSN 1383-5866, https://doi.org/10.1016/j.seppur.2023.125001. https://www.sciencedirect.com/science/article/pii/S1383586623019093
[15] Ouro-Salim O., Urban mining of e-waste management globally: Literature review, Cleaner Waste Systems, Volume 9, 2024, 100162, ISSN 2772-9125, https://doi.org/10.1016/j.clwas.2024.100162. https://www.sciencedirect.com/science/article/pii/S2772912524000344
[16] Faschingleitner J., Höflinger W., Evaluation of primary and secondary fugitive dust suppression methods using enclosed water spraying systems at bulk solids handling, Advanced Powder Technology, Volume 22, Issue 2, 2011, Pages 236-244, ISSN 0921-8831, https://doi.org/10.1016/j.apt.2010.12.013. https://www.sciencedirect.com/science/article/pii/S0921883110002554
[17] Barraza F. P., Thiyagarajan D., Ramadoss A., Manikandan V.S., Dhanabalan S. S., Venegas Abarzúa C., Soloaga P. S., Nazer J. C., Morel J. M., Thirumurugan A., Unlocking the potential: Mining tailings as a source of sustainable nanomaterials, Renewable and Sustainable Energy Reviews, Volume 202, 2024, 114665, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2024.114665. https://www.sciencedirect.com/science/article/pii/S1364032124003915
[18] Hilson G., Small-scale mining, poverty and economic development in sub-Saharan Africa: An overview, Resources Policy, Volume 34, Issues 1–2, 2009, Pages 1-5, ISSN 0301-4207, https://doi.org/10.1016/j.resourpol.2008.12.001. https://www.sciencedirect.com/science/article/pii/S0301420708000834



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IN SITU REHABILITATION OF AGING PUBLIC WATER SUPPLY WELLS

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Abstract: The main causes of well aging and consequently performance decline are incrustation from mineral scaling, biofilm development, and microbial fouling. The presented research was conducted with the aim of examination and comparison of advantages and disadvantages of different *in situ* rehabilitation methods for improving well yield and water quality. Mechanical approaches which include wire brushing, jetting, and surging physically remove deposits and clogs, while chemical techniques utilize acid dissolution, oxidizing and reducing agents, and chelating compounds. Chemical techniques effectively treat iron, manganese, and calcium scales. The novel biological treatments, including enzyme-based biofilm removal and bacteriophage applications, offer a promising approach to selective and sustainable prevention of fouling. As a result, the mechanisms, advantages, and limitations of each method along with safety and regulatory considerations for their use in potable water systems are analyzed. The paper emphasizes the need for well-adapted, integrated approaches to maintain long-term functionality and protect and safe public health.
Key words: Well rehabilitation, incrustation, biofilm, water supply wells

INTRODUCTION

Over time the accumulation of mineral and biological deposits in public water supply wells leads to performance and yield decline, the process commonly known as well ageing or incrustation. Fouling usually includes the formation of ochre deposits, from iron and manganese oxides, calcium carbonate scaling, and development of biofilms due to iron bacteria and other microorganisms.
Such deposits narrow screen openings, clog adjacent aquifer pore spaces, and restrict water inflow, leading to reduced yield, impaired water quality, and increased operational costs. The primary contributors to well fouling are iron and manganese oxides, which precipitate as reddish-brown or black crusts on well infrastructure. Calcium carbonate scaling, formed from the precipitation of carbonate-rich groundwater minerals, creating hard, calcareous deposits. The slime produced by microbial communities includes a gelatinous extracellular material that can trap metals and other particles. These components often co-occur, creating complex and persistent incrustations that resist removal. In response, water utilities employ a combination of *in situ* rehabilitation techniques that restore well performance without necessitating complete reconstruction. Such methods must be evidently effective, safe for drinking water systems, and ideally supported by field validation or peer-reviewed literature.
We reviewed techniques alongside new developments aimed at improving well rehabilitation methods. It discusses their mechanisms of action, field applications, benefits, and limitations. The objective of conducted review is to offer a technically sound reference for utility engineers and hydrogeologists involved in maintaining the longevity and efficiency of public water supply infrastructure.

MATERIAL AND METHODS

To review the advantages and disadvantages of available regeneration methods, presented research encompassed comprehensive synthesis of established field practices, scientific research, industry manuals, and technical reports related to the *in situ* rehabilitation of aging

water supply wells. The review includes both conventional techniques and innovative technologies, evaluated considering practical applicability, safety, and regulatory compliance. Standard operating procedures were drawn from established guidelines published by organizations such as Penn State Extension [1], the American Water Works Association (AWWA) [7], and industry publications like the Water Well Journal [2]. These were complemented by peer-reviewed studies focused on removing mineral deposits, such as carbonate scale and iron or manganese oxides [4,5], as well as research on the use of chemical agents like oxidants and chelating compounds for cleaning wells [3,5,7]. In addition, recent advances in biological treatment methods, including enzyme-based cleaning and bacteriophage applications, were considered for their potential in controlling biofilms [6]. Safety and regulatory aspects were reviewed using drinking water standards such as NSF/ANSI Standard 60, which sets the criteria for allowable treatment chemicals in potable water systems.

Methodological Approach

The three main well regeneration categories, which represent the principal approaches to well rehabilitation: mechanical, chemical, and biological (innovative) techniques are differentiated. Mechanical *in situ* techniques consider physical breaking up and removing mineral and biological buildup inside the well, through direct agitation, brushing, jetting, or hydraulic impulses. Chemical methods comprise the use of acids, oxidants, reducing agents, and chelants to dissolve or dislodge incrustation and sanitize biofouled surfaces. Innovative biological strategies, including enzymatic treatments and bacteriophage applications, represent a growing area of interest for selective and environmentally compatible biofilm control.
The distinguished categories were critically assessed considering their mechanism of action and primary fouling targets (e.g., carbonate scaling, iron oxide coatings, or biofilms). The results of laboratory studies and field-scale implementations indicated the effectiveness of applied methods. The consideration of operational safety and compatibility with potable water standards was also analyzed, along with attention to infrastructure integrity and potential impacts on well components. The review also accounted for regulatory and environmental aspects, to determine the feasibility of each approach within public water supply systems. Special emphasis was placed on practical field guidelines and multi-method rehabilitation sequences commonly used by utilities. This structured, multidisciplinary approach provides a solid basis for understanding how *in situ* well rehabilitation techniques function individually and in combination, and under what conditions each method is most appropriate.

RESULTS AND DISCUSSION

This section presents a comprehensive overview of *in situ* rehabilitation techniques used in public water supply wells, organized into mentioned categories: mechanical methods, chemical treatments and innovative biological approaches. In addition to these categories, regulatory constraints are also considered, since these are public supply wells. The evaluation of each method considers its working principle, effectiveness in the field, strengths, and potential constraints.

Mechanical Rehabilitation Techniques

Mechanical methods are often the first line of defense in well rehabilitation and remain the most widely known and commonly applied regeneration approach. In considers mechanical action and physical disturbance of mineral and biological deposits without introducing chemical agents. These techniques are long-established and widely field-tested and form the foundation of most well maintenance programs.
One of the most commonly applied mechanical cleaning methods involves the use of wire or nylon brushes attached to drill rods, which are lowered into the well to physically scrub the

casing and screen surfaces. This approach is very effective in physically removing formed rust, mineral scale, and biofilm from wells with uniform diameters. To enhance the efficiency of debris removal, brushing is often combined with swabbing or simultaneous pumping, which facilitates the extraction of dislodged material from the wellbore [1,2]. Another widely used physical method is high-pressure jetting, where water is injected through specialized nozzles onto the well screen and adjacent formation. This technique effectively dislodges mineral deposits and hardened biofilms by hydraulic flushing. When applied at carefully regulated pressures, jetting can clean well components without compromising the integrity of the gravel pack or casing infrastructure [1]. Another widely used in situ method is surging, which creates turbulent water movement inside the well. This is typically done by repeatedly reversing the flow using a surge block or by quickly turning the pump on and off. The resulting agitation helps to dislodge mineral particles, bacterial slimes, and sediment from the screen and casing surfaces. To remove the mobilized debris, air-lift pumping is often employed. This method introduces compressed air into the well to lift water and suspended solids to the surface. Surging and air-lift pumping are frequently used together, offering a cost-effective means of mechanical cleaning and improving the distribution and penetration of subsequently applied chemical treatments [1]. In cases of severe clogging or significantly reduced well yield, energy-based methods such as hydrofracturing and impulse treatments may be required. For example, liquid carbon dioxide can be injected into the well, where it rapidly expands and creates a series of pressure pulses or micro-explosions. These impulses generate mechanical disruption within the clogged formation while simultaneously forming carbonic acid through CO_2 dissolution, which enhances the chemical breakdown of carbonate scale. Compared to conventional brushing or jetting, these methods can reach deeper into the aquifer matrix and are typically employed when shallower in-well techniques prove insufficient.

Mechanical rehabilitation methods offer several advantages in the context of well maintenance. They eliminate the risk of chemical contamination, making them particularly suitable for drinking water wells. Most techniques are compatible with a wide range of well designs and can be safely repeated as part of routine maintenance. These methods are especially effective in physically removing thick biofilms, rust deposits, and debris from clogged screens.

The limitations of mechanical approaches are that they are generally ineffective at fully dissolving hardened mineral scale and do not prevent bacterial recolonization, which can occur shortly after treatment. Their action is confined to surfaces that are directly accessible, leaving deeper zones of the formation untreated. Additionally, improper application may lead to mechanical damage, highlighting the importance of operator experience and equipment control during implementation.

Chemical Rehabilitation Techniques

Chemical rehabilitation techniques are used to dissolve incrustation, destroy biofilms, and neutralize contaminants that cannot be removed mechanically. To ensure these methods are highly effective and safe, it's essential to carefully formulate the treatment, apply the right dose, and thoroughly flush the system afterward. Treatments considering acid application are widely used in well rehabilitation to dissolve mineral incrustations and improve hydraulic performance. Hydrochloric acid (HCl), typically applied at concentrations between 5% and 15%, is the most commonly used agent for dissolving calcium carbonate scale and iron oxide crusts [4]. Sulfamic and acetic acid can be useful alternatives, depending on site-specific conditions and infrastructure compatibility. These treatments significantly lower the pH (< 2), causing rapid dissolution of scale and, in some cases, indirectly reducing biofilm presence by disrupting the mineral substrate in which microbial communities reside. Optimal results are achieved when acid contact time is maintained for 24 to 48 hours, often accompanied by intermittent surging to improve acid distribution and mobilize loosened material. Field experience indicates that adequate acid treatments often lead to significant improvements in well yield and specific capacity [1,4,5]. Oxidizing biocides are commonly employed to disinfect wells and control biofilm-related clogging. Strong oxidative potential of sodium hypochlorite (NaOCl), hydrogen peroxide (H_2O_2), and chlorine dioxide (ClO_2) is frequently used due to their aggressiveness

and efficacy [1]. High-dose chlorination, often known as shock treatment, considers the use of chlorine concentrations in dose from 500 to 2,000 mg/L. It is particularly effective in eliminating iron bacteria and disrupting microbial films. Hydrogen peroxide not only serves as a disinfectant but also generates oxygen gas bubbles that promote mechanical agitation and physical detachment of biofilms from well surfaces. Chlorine dioxide is valued for its stability across a wider pH range and for producing fewer disinfection byproducts compared to traditional chlorination methods, making it suitable for sensitive applications where water quality preservation is critical. Reducing agents and chelating compounds play an important role in the chemical rehabilitation of wells affected by iron and manganese oxide fouling. Sodium dithionite ($Na_2S_2O_4$) is a potent reductant that converts insoluble ferric (Fe^{3+}) and manganese (Mn^{4+}) oxides into their soluble ferrous (Fe^{2+}) and manganous (Mn^{2+}) forms, facilitating their removal through subsequent pumping [5]. Chelating agents such as ethylenediaminetetraacetic acid (EDTA) and polyphosphates are employed to bind dissolved metal ions, thereby preventing their reprecipitation within the well structure. These substances are often mixed with acids, surfactants, or dispersing agents in special cleaning solutions made to work better in real-world conditions [2,5]. Chemical treatments offer significant advantages over purely mechanical methods, particularly in their ability to dissolve mineral deposits and microbial films that cannot be eliminated by physical agitation. Acidic formulations act rapidly to dissolve carbonate and iron oxide scale, oxidizing agents sanitize the well environment and degrade biofilms, while reducing agents effectively solubilize otherwise persistent metal oxides. These mechanisms, when properly applied, can result in significant improvements in well performance and water quality.

However, chemical treatments also present operational challenges and safety considerations. Acids, while effective, can corrode metal well components if not carefully managed. Oxidizing agents may lead to the formation of disinfection byproducts, especially in the presence of organic matter, while reducing agents require strict pH control to remain effective. Additionally, thorough post-treatment flushing is critical to remove residual chemicals and avoid contamination of the potable water supply.

Innovative Biological Approaches

As the water sector moves toward more sustainable practices, interest is growing in biological methods for rehabilitating public water supply wells. These methods are being explored as alternatives to conventional chemical treatments, especially because they may offer safer and more targeted ways to manage biofouling.

Biological approaches typically aim at microorganisms that form biofilms, using either enzymes or bacteriophages. Enzymes like dispersin B and certain glycosidases can break down the extracellular matrix that holds biofilms together. These compounds are generally considered as non-toxic, are effective in neutral pH conditions, and don't pose risks to well structures or water quality. In lab settings, combining enzymatic treatment with mechanical surging has led to more than 90% biofilm reduction (result under controlled conditions).

Another line of research involves bacteriophages, viruses that infect and destroy specific bacteria. This method is promising for controlling prevalent iron-related biofouling caused by bacteria such as *Gallionella* and *Leptothrix*. Once inside the system, bacteriophages multiply within their target bacteria and eventually cause them to rupture, which helps reduce microbial buildup. While still in the early stages of development, initial field examinations have shown a decrease in bacteria counts and reduced clogging potential. However, questions remain about regulatory approval, long-term effects, and the specificity of these viruses to their intended bacterial hosts.

Biological treatments have shown several advantages. They are highly selective, leaving non-target organisms unaffected and avoiding chemical residues that could harm groundwater. Their environmental profile makes them well-suited for sensitive aquifers or protected zones. Used alongside mechanical or chemical methods, they may also become a useful part of broader, integrated strategies for maintaining wells clean over the long period.

Figure 1 provides an overview of *in situ* rehabilitation techniques currently being explored for aging public water supply wells.

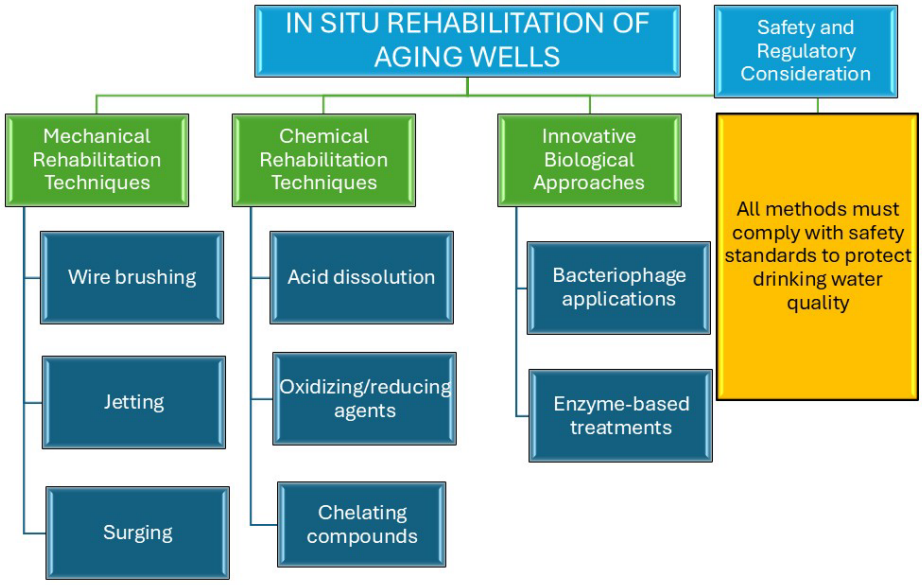


Fig. 1. *Overview of In Situ Rehabilitation Techniques for Aging Public Water Supply Wells*

It should be emphasized that innovative biological approaches are still in the research and development phase, and their widespread implementation depends on several factors. Their effectiveness is highly dependent on the composition of the microbial community and site-specific well conditions. In addition, regulatory acceptance remains limited, with few approved protocols for use in potable water systems. Standardized application procedures and long-term performance data are still not available, emphasizing the need for further examination and validation before routine field deployment can be recommended.

Safety and Regulatory Considerations

All *in situ* rehabilitation treatments must comply with strict and rigorous drinking water safety standards to protect both public health and environmental quality. For example, in the United States, chemicals introduced into potable water systems are required to meet the allowable levels and purity requirements for drinking water treatment chemicals defined in NSF/ANSI Standard 60, developed by the National Sanitation Foundation (NSF) and the American National Standards Institute (ANSI) [1,8]. While Serbia does not formally adopt this standard, it provides a widely recognized international criterion for chemical safety. In practice, all treated wells should be thoroughly flushed until water quality stabilizes and key parameters, including, among others, pH, turbidity, residual disinfectants, and concentrations of dissolved metals, return to values compliant with national drinking water regulations. Chemical safety during application is a critical point. Acids and oxidants must be handled using appropriate personal protective equipment, and their application must be carefully controlled to prevent operator exposure or corrosion of well infrastructure. Wastewater generated during rehabilitation contains elevated concentrations of metals, residual disinfectants, or other reactive compounds. New biological agents like enzymes or bacteriophages need careful review by public health authorities. To be considered for use in public water systems, they must be shown to be safe, effective, and not persistent in the treated water. Successful and safe implementation of well rehabilitation strategies requires not only technically sound methods but also skilled personnel, environmental risk management, and regulatory alignment to ensure that the well can be returned to service without adverse impact.

CONCLUSION

In situ rehabilitation of aging public water supply wells is a well-established but still continuously advancing field that brings together years of field experience and modern scientific progress. As wells age, they are increasingly susceptible to hydraulic inefficiency and water quality degradation caused by mineral incrustation, biofouling, and physical clogging of the well screen and surrounding aquifer matrix. Effective restoration of well performance requires the strategic application of multiple techniques, each selected based on the specific fouling mechanisms present. Mechanical interventions remain essential for mobilizing and removing deposits from accessible well surfaces. Their effectiveness is often enhanced when combined with chemical treatments, which provide deeper penetration and dissolution of carbonate scales, iron oxides, and biofilm matrices that are otherwise resistant to physical removal. Chemical strategies, including acidification, oxidizing and reducing agents, and chelating compounds, are widely validated and remain central to most rehabilitation programs. Biological methods, particularly enzymatic treatments and phage application are gaining interest as environmentally sustainable alternatives for selective biofilm control. Although still in the research, these approaches offer promising synergies with conventional treatments and may shape the future of well maintenance. Throughout all stages of rehabilitation, adherence to safety protocols and regulatory standards is critical. Chemicals must meet drinking water criteria, and all treatment residuals must be properly neutralized and disposed of in compliance with environmental protection laws. Routine monitoring, preventive maintenance, and timely intervention further reduce the frequency and severity of well degradation. A multidisciplinary and adaptive approach remains essential for ensuring the long-term sustainability of public water supply infrastructure.

REFERENCES

[1] Penn State Extension. (2021). *Maintenance and Rehabilitation of Water Wells*. Pennsylvania State University.
[2] National Ground Water Association. (2016). *Residential Well Cleaning: What You Need to Know*. Retrieved from NGWA.
[3] Patil, S., Maity, A., & Balhoff, M. (2023). Carbon utilization and storage through rehabilitation of groundwater wells. EarthArXiv. https://doi.org/10.31223/X5ZP9S
[4] Duan, S., Liu, Z., Zhuo, H., Wang, T., Liu, J., Wang, L., Liang, J., Han, J., Huang, Y., & Li, Q. (2020). Hydrochloric acid corrosion induced bifunctional free-standing NiFe hydroxide nanosheets towards high-performance alkaline seawater splitting. *Nanoscale, 12*(42), 21876–21884. https://doi.org/10.1039/D0NR05444D
[5] Houben, G. J. P. M., & Treskatis, M. (2002). Iron oxide incrustations in wells. Part 2: Chemical dissolution and modeling. *Journal of Contaminant Hydrology*, *55*(3–4), 181–212.
[6] Tian, F., Li, J., Nazir, A., & Tong, Y. (2021). Bacteriophage – A promising alternative measure for bacterial biofilm control. *Infection and Drug Resistance, 14*, 205–217. https://doi.org/10.2147/IDR.S290093
[7] American Water Works Association (AWWA). (2017). *Standard Practices for the Rehabilitation of Water Wells* (Manual M21).

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STRONTIUM IN GROUNDWATER AS AN INDICATOR OF DEEP AQUIFER MIXING

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Abstract: Strontium (Sr) is a naturally present trace element in groundwater, and its concentration can vary widely depending on geology, hydrochemistry, and climate. This study integrates the geochemical behaviour of Sr in groundwater environment, emphasizing its sources, mobility, and potential as a tracer of deep groundwater mixing. Sr usually originates from the dissolution of carbonate, sulphate, and silicate minerals, with carbonate aquifers often contributing the highest concentrations. Its mobility is governed by pH, competing ions, ionic strength, and residence time, while redox conditions exert only indirect effects through mineral solubility. Typical concentrations range from <1 mg/L in shallow fresh recharge zones to >10 mg/L in deep, mineralized, or saline systems. High Sr levels in shallow aquifers may indicate deep groundwater input, particularly when accompanied by elevated total dissolved solids or other tracers. The research highlights Sr's utility as a conservative tracer when a significant geological difference exists between shallow and deep aquifers. Understanding the concentration data requires considering local geochemical processes, co-precipitation and evaporation. When used in combination with other hydrochemical indicators, Sr concentration can present a valuable tool for identifying groundwater mixing and tracing water-rock interactions over varying spatial and temporal scales.
Key words: groundwater mixing, strontium, tracer

INTRODUCTION

Sr is an alkaline earth metal (Group 2) that commonly occurs as a trace element in rocks, soils, and natural waters [1]. Strontium is a widespread constituent in groundwater, as evidenced by a comprehensive survey of U.S. aquifers that detected its presence in 99.8% of analysed samples [1]. It is typically present as the divalent cation Sr^{2+} in solution, and its concentration depends on water-rock interactions. The primary sources of Sr in groundwater are the dissolution of minerals that contain Sr either as a constituent or by isomorphic substitution. The most studied Sr-bearing minerals include carbonates, sulphates, and silicates. In carbonate minerals such as calcite and dolomite, strontium commonly substitutes for calcium, leading to elevated Sr concentrations in groundwater from carbonate aquifers [2]. Among sulphate minerals, celestite ($SrSO_4$) directly contributes strontium, while gypsum ($CaSO_4 \cdot 2H_2O$) and anhydrite often contain Sr as an impurity. Silicate minerals, including feldspars ($KAlSi_3O_8$ – $NaAlSi_3O_8$ – $CaAl_2Si_2O_8$) and clays, may also release Sr during the weathering of aluminosilicate rocks. This process is typically slower and yields lower concentrations of Sr compared to carbonates [3]. Under natural conditions, typical Sr concentrations in fresh groundwater are on the order of tenths to a few mg/L. A global survey of freshwater indicates background Sr levels around 0.5 - 1.5 mg/L [2]. In many young, shallow aquifers with limited mineral contact, Sr remains <1 mg/L (for example, the median Sr in above 4,800 U.S. groundwater samples was 0.225 mg/L) [1]. Groundwater in carbonate-rich aquifers typically contains the highest strontium concentrations, due to mineral dissolution processes. Similarly, aquifers in arid regions can exhibit elevated Sr levels as a result of evaporative concentration [1]. While low Sr is common in dilute recharge, values of several mg/L or more may occur where geology and climate favour Sr enrichment.

MATERIAL AND METHODS

This study synthesizes current geochemical understanding of Sr behaviour in groundwater environment by integrating hydrochemical data from global case studies and previously published datasets, primarily from the U.S. Geological Survey (USGS), peer-reviewed literature, and regional hydrogeological surveys. Strontium concentrations and associated hydrochemical parameters were examined across various aquifer settings, including carbonate-rich, arid, and saline environments. Special attention was given to aquifer depth, residence time, mineral composition, redox conditions, and evaporative influences as controlling factors for Sr mobility and distribution.

RESULTS AND DISCUSSION

Strontium concentrations in groundwater exhibit systematic variations across different aquifer types and hydrogeological settings. Analysis of published data reveals a clear trend of increasing Sr levels with longer residence time, higher mineralization, and the influence of saline or evaporative processes.

In shallow, fresh recharge zones, typically in humid climates and karstic terrains, Sr concentrations are generally low, ranging from 0.1 to 0.5 mg/L. These systems exhibit minimal water-rock interaction and limited dissolution of Sr-bearing minerals. In contrast, shallow aquifers located in arid or semi-arid environments show significantly higher concentrations, between 1 and 5 mg/L, primarily due to evapoconcentration, irrigation return flow, and longer groundwater residence time.

Deep, confined aquifers in carbonate or evaporite-rich formations often contain Sr concentrations exceeding 4 mg/L, with typical values between 1 and 10 mg/L. This is attributed to prolonged contact with Sr-bearing carbonates and sulphates. The highest concentrations, often ranging from 5 to over 20 mg/L, are observed in deep saline or fossil groundwater, particularly in areas affected by upwelling brines or ancient seawater intrusion.

An overview of these patterns is shown in Table 1, which lists typical Sr concentrations and the corresponding geochemical conditions for each aquifer type.

Table 1. *Representative strontium concentrations across different aquifer settings*

Aquifer Setting	Typical Sr Concentration	Geochemical Context and Source Description
Shallow, fresh recharge (humid climate, short flow path; e.g., karst springs)	≈0.1–0.5 mg/L (typically <1 mg/L)	Limited water-rock interaction leads to low Sr mobilization. Sr concentrations reflect the geochemistry of shallow, young groundwater. [1]; [4]
Shallow, arid or evaporative (unconfined aquifers, high evapotranspiration or irrigation)	≈1–5 mg/L	Increased residence time and evapoconcentration enhance Sr levels, often along with higher total dissolved solids (TDS), Cl^-, and Na^+. [1]
Deep, long-residence freshwater (confined carbonate or evaporite aquifers)	≈1–10 mg/L (often >4 mg/L)	Prolonged contact with Sr-bearing minerals such as carbonates and sulphates leads to higher Sr concentrations. [1]; [4]

Deep, saline or fossil groundwater (brine or paleo-seawater mixing)	5–20 mg/L	High Sr reflects mixing with ancient marine-derived waters or upwelling brines. Modern seawater contains ~8 mg/L Sr. [1]

Sr Mobility and Controlling Hydrochemical Factors

Once released from minerals, Sr^{2+} behaves geochemically similarly to Ca^{2+} in groundwater. Its mobility and concentration are influenced by several the most influential hydrochemical parameters. Groundwater pH controls and significantly impacts the dissolution and precipitation of carbonate minerals. Under neutral to moderately acidic conditions, calcite and dolomite dissolve, releasing Sr^{2+} alongside Ca^{2+}. Sr mobility peaks during early water-rock interactions. As calcite saturation is reached, Sr may co-precipitate or become incorporated into carbonate minerals, particularly in systems with high carbonate alkalinity. In high-pH environments, strontianite ($SrCO_3$) or mixed Ca-Sr carbonates may form, decreasing Sr concentrations in solution.
Elevated Ca^{2+} can induce common ion effects and promote calcite precipitation, which also removes Sr. Due to its larger ionic radius, Sr^{2+} is less readily incorporated into calcite, often remaining longer in solution. Sr/Ca ratios in groundwater can reveal selective incorporation patterns. Strontium can also be temporarily retained through ion exchange with clays and freshly formed minerals, but once those exchange sites become saturated, Sr tends to remain in solution [3].
Sr remains in the +2 oxidation state and is largely redox-independent. However, redox can influence cooccurring elements such as sulphate. In reducing environments, sulphate reduction may dissolve Sr-bearing sulphate minerals. In contrast, under oxidizing conditions, precipitation of celestite ($SrSO_4$) may occur if sulphate and Sr concentrations are high [5].
There is significant positive correlation between TDS and elevated Sr levels. Saline environments, whether from marine intrusion, evaporation, or brines, maintain Sr in solution due to complexation and suppressed mineral precipitation [1]. Marine-derived groundwater or paleoseawater often contributes significantly to increase of Sr concentrations, with ocean water containing ~8 mg/L Sr.
Prolonged water-rock interaction enhances Sr mobilization in water solution. While carbonates rapidly release Sr, silicate minerals contribute more gradually. Older, deeper groundwater typically shows higher Sr due to cumulative dissolution over time.
High Sr levels in shallow aquifers often serve as a geochemical indicator of mixing with deeper groundwater. Deep carbonate systems often exceed 4 mg/L Sr due to extended interaction with Sr-bearing lithologies. If such indications are found in overlying shallow wells, upward leakage may be occurring. In semi-arid regions, evaporation concentrates Sr and other solutes in shallow aquifers. These elevated levels may mimic deep water inputs but can be distinguished through isotopic analysis and simultaneous determination of chloride, sulphate, and TDS [2], [6]. The most distinct source of high Sr is up-coning of deep, saline groundwater. These waters are enriched in Sr due to ancient seawater origins and extensive geochemical aging.

Strontium Isotopes (^87Sr/^86Sr) as Tracers of Aquifer Mixing

Strontium has four stable isotopes, of which ^{87}Sr is radiogenic and formed through the decay of ^{87}Rb. Because the $^{87}Sr/^{86}Sr$ ratio varies depending on lithology and geological age, it can be used as a powerful natural tracer for groundwater source and mixing processes identification. Groundwater receives its isotopic signature through water-rock interaction, and variations in $^{87}Sr/^{86}Sr$ reflect differences in mineralogy and rock age across aquifer systems. For example, studies in the Yucatan Peninsula demonstrated that $^{87}Sr/^{86}Sr$ ratios can clearly distinguish between freshwater recharge and mixing with seawater or older marine-derived waters [7]. In

fractured granite aquifers in Korea, Sr isotopic ratios revealed limited mixing between deep geothermal and shallow meteoric waters, indicating slow exchange and long residence times [8].

Strontium isotopes are especially valuable for distinguishing deep from shallow groundwater origin in systems where the results of conventional tracers may be ambiguous. In the Eastern Snake River Plain (Idaho), combining $^{87}Sr/^{86}Sr$ ratios with uranium isotopes enabled quantification of mixing between distinct aquifer zones [9]. Likewise, in Taiwan's Choushui River alluvial fan, $^{87}Sr/^{86}Sr$ ratios differentiated paleo-seawater contributions from recent recharge, highlighting their utility in coastal aquifers [10].

In areas influenced by salinity or brines, the $^{87}Sr/^{86}Sr$ ratio often shifts away from modern seawater values (≈0.7092), pointing to older marine inputs or long-term geochemical evolution. These variations can help distinguish whether elevated Sr comes from ancient seawater mixing, evaporation, or the dissolution of local minerals [7], [10].

CONCLUSION

Sr exhibits several geochemical characteristics that support its use as a tracer for detecting deep groundwater contributions to shallow aquifers. Its solubility, conservative behaviour under most redox and biological conditions, and typically distinct concentration gradient between shallow and deep groundwater make it a useful indicator of mixing processes. In systems where deep, mineralized groundwater with elevated Sr concentrations enter shallow zones with low Sr background, even small mixing inputs can produce detectable shifts in concentration.

Although elevated Sr levels can suggest a deep source, they may also result from local processes such as evaporation or lithological release, making it difficult to distinguish. Shallow aquifers in arid regions or carbonate-rich regions may naturally contain elevated Sr, making it difficult to distinguish deeper inflow impacts from local influences. Under specific geochemical conditions, such as sulphate-rich or carbonate-saturated environments, Sr may precipitate as celestite ($SrSO_4$) or co-precipitate with calcite, reducing its dissolved concentration and affecting its tracer behaviour.

Despite these limitations, Sr remains a valuable component in a multi-tracer framework. When there is a complementary interpretation with other indicators like Cl^-, Br^-, Li^+, or isotopic ratios (e.g., $^{87}Sr/^{86}Sr$), Sr concentrations can provide robust evidence for identifying deep groundwater mixing. Elevated Sr in shallow aquifers, particularly when accompanied by increased total dissolved solids, specific ions, or isotopic signatures, strongly suggests influence from older, deeper, or more mineralized groundwater sources.

Strontium proves to be a feasible and effective tracer for identifying deep groundwater contributions, particularly when interpreted within a broader hydrogeochemical context.

REFERENCES

[1] Musgrove, M. (2021). The occurrence and distribution of strontium in U.S. groundwater. Applied Geochemistry. https://doi.org/10.1016/j.apgeochem.2020.104867

[2] Li, D., Gan, S., Li, J., Dong, Z., Long, Q., Qiu, S., Zhou, Y., & Lu, C. (2021). Hydrochemical characteristics and formation mechanism of strontium-rich groundwater in Shijiazhuang, North China Plain. Journal of Chemistry, 2021, Article ID 5547924, 10 pages. https://doi.org/10.1155/2021/5547924

[3] Malov, A. I. (2024). The Conditions for the Formation of Strontium in the Water of Ancient Silicate Deposits Near the Arctic Coast of Russia. Water, 16(17), 2369. https://doi.org/10.3390/w16172369

[4] U.S. Geological Survey (USGS). (2010). The occurrence and distribution of strontium in U.S. groundwater (Scientific Investigations Report 2010–5079). U.S. Department of the Interior. https://pubs.usgs.gov/sir/2010/5079

[5] Clauer, N., Techer, I., & Chaudhuri, S. (2017). Geochemical tracing of potential hydraulic connections between groundwater and run-off water in northeastern Kansas, USA. Hydrology, 4(4), 56. https://doi.org/10.3390/hydrology4040056
[6] U.S. Geological Survey (USGS). (2020). The occurrence and distribution of strontium in U.S. groundwater. U.S. Department of the Interior. https://www.usgs.gov/centers/ogw/science/occurrence-and-distribution-strontium-us-groundwater
[7] McKay, J., Lenczewski, M., & Leal-Bautista, R. M. (2020). Characterization of flowpath using geochemistry and ^87Sr/^86Sr isotope ratios in the Yalahau region, Yucatán Peninsula, Mexico. Water, 12(9), Article 2587. https://doi.org/10.3390/w12092587
[8] Lee, S.-G., Kim, T.-K., Lee, J.-S., Lee, T.-J., Cho, B.-W., & Koh, H.-J. (2008). Geochemical implication of ^87Sr/^86Sr ratio of high-temperature deep groundwater in a fractured granite aquifer. Geochemical Journal, 42(5), 429–441
[9] Rattray, G. W., & Paces, J. B. (2020). Evaluation of hydrologic processes in the Eastern Snake River Plain Aquifer using uranium and strontium isotopes, Idaho National Laboratory, Eastern Idaho (Professional Paper 1837–D). U.S. Geological Survey. https://doi.org/10.3133/pp1837D
[10] Huang, H.-W., Huang, S.-T., Wang, R.-M., Chen, W.-F., Chung, C.-H., & You, C.-F. (2024). Strontium isotopic composition as tracers for identifying groundwater recharge sources in the Choushui River alluvial plain, western Taiwan. Water, 16(15), 2151. https://doi.org/10.3390/w16152151

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GREEN NEW DEAL FOR CLIMATE CHANGE

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Abstract: Technological fixes, the purchase of green products, and the organization of emission trading schemes merely postpone the transformation of the existing socio-economic reality. If green technological innovations are driven primarily by the maximization of profit, it is unlikely that they will lead to the resolution of global climate change. In fact, the use of more benign technologies only means that humanity will continue along the same path that has already led to civilizational decline. Hence, a Green New Deal for climate change is necessary—an alternative vision of political, social, and economic thinking that will enable a synthesis of recovery from the current recession and substantial investments in renewable energy sources and a sustainable economy based on them. Confronting global climate change will disrupt all the rules of the free market game, rebuild the public sphere, redirect privatization, reduce consumption, reintroduce long-term planning, and impose regulations to control and tax corporations.
Key words: neoliberal capitalism, ideology, entrepreneurial state, Green New Deal

INTRODUCTION

The global neoliberal system is failing. Civilization as we know it is doomed to collapse, as ecological catastrophes, such as global flooding, threaten the very foundations of civilization itself. "**We must notice that the objective victory of global capitalism is a destructive, aggressive practice**," writes Alain Badiou [1].
Nature has become the object of unlimited, total exploitation because boundless imperialism is never satisfied. Humanity's dominion over planet Earth has no precedent in previous epochs of Nature's history, in which other animals represented the highest forms of life. Their appetites were limited to their survival needs. However, Max Horkheimer argues that greed is not inherent to the human species but emerges within the values of capitalist society. As he writes, "**Man's greed to extend his power over the two infinities, the microcosm and the universe, does not arise directly from his own nature, but from the structure of society. The totalitarian assault of the human race on everything that lies beyond itself derives more from interhuman relations than from innate human qualities**" [2]. Paradoxically, through the exponential growth of our freedoms and powers, that is, "**our growing capacity to transform the nature around us even to the point of destabilizing the basic geological foundations of life**" [3], we in fact limit our freedoms, a phenomenon made evident by the consequences of global warming.
State mechanisms lie at the very core of capital reproduction, ensuring its uninterrupted accumulation through expropriation via educational, ecological, social, economic, legal, and other mechanisms. Therefore, resistance to global neoliberal capitalism cannot occur within the framework of the existing late-capitalist consumer culture.
Nevertheless, despite the global triumph of capitalism, many trends signal the deep, advanced disintegration of the system. The neoliberal economic cycle, initiated in the 1970s and exemplified by Yanis Varoufakis' concept of the Global Minotaur, which drove the global economy into financial collapse in 2008, is unraveling. According to Žižek, Marx was correct regarding the "final crisis" of capitalism, which we have now entered: "**In broad daylight, capitalism openly disintegrates and transforms into something else. We fail to perceive this ongoing transformation due to our immersion in ideology**" [3].

MATERIAL AND METHODS

The primary question addressed in this study is the inadequacy of the neoliberal capitalist framework in effectively confronting climate change. Addressing this issue requires a fundamental transformation of social and economic policies, alongside the mobilization of global collective efforts to ensure a sustainable future. In light of the identified problem, the following research objectives have been formulated:

1. To critically assess the neoliberal capitalist ideological system and its systemic shortcomings in providing effective responses to the challenges posed by climate change.
2. To evaluate alternative economic models, with particular attention to the concept of the "Green New Deal" as a sustainable framework for facilitating the green transition and promoting sustainable development.
3. To propose comprehensive strategies and policies aimed at transforming the economy toward sustainable practices, including the transition to renewable energy sources, the development of sustainable infrastructure, and the adoption of environmentally responsible practices.
4. To identify key stakeholders and formulate recommendations to foster long-term collaboration among governmental institutions, the private sector, civil society, and international organizations in response to the climate crisis.

The Green New Deal

"We are moving toward a society that will ultimately be completely different from today."
Anthony Giddens [4]

Given the scale of the global climate crisis we face, minimal taxation of polluters or market-based regulation of carbon emissions is insufficient in the context of transforming the entire economy. Individual decisions regarding personal consumption will not make a significant contribution when considering the magnitude of changes required. Free-market capitalism, as an economic system of unlimited consumption and environmental depletion, is the epicenter of the climate crisis. It is necessary to draw historical parallels with the *Marshall Plan* (The Marshall Plan was inaugurated in June 1947, with a rationale that aligns closely with the theoretical views expressed at the beginning of the 18th century by the Italian mercantilist Serra, according to whom the production of raw materials and industrial goods is subject to different laws.) or Franklin Roosevelt's New Deal, as they remind us of times when humanity was capable of thinking on such large-scale socio-economic changes*: "***This means a return to economic planning based on collective priorities rather than corporate profitability**" [5].

A crisis of this magnitude must change everything. A complete transformation of all national and global economies, which have already failed most people on this planet, must focus on climate imperatives: "**…some parts of the economy will have to grow, some shrink, and some disappear**," asserts Naomi Klein [6]. The "Green New Deal" represents a vision of political, social, and economic thinking that will ensure a combination of recovery from the current recession and large-scale investment in renewable energy and the sustainable economy it enables. All free-market rules must be broken, the public sphere rebuilt, privatization redirected, consumption reduced, long-term planning reintroduced, and corporations regulated and taxed.

It is evident that, due to the demands for transforming every aspect of our economy, many powerful interests in the industrial and financial sectors would resist these changes. This primarily concerns multinational corporations that extract fossil fuels and have for many years funded misinformation campaigns regarding the reality of global climate change.

Mariana Mazzucato also agrees that addressing the climate crisis requires transforming the global economy. Innovative transformations will represent one of the greatest changes

humanities has ever attempted. However, it is necessary to shift from short-term profit-oriented thinking to achieving long-term results and profits: **"Industrial strategies do not only need different goals; they need missions**" [7]. Missions akin to the Apollo 11 mission, or a green transformation with Roosevelt-scale investments, are essential to combat climate change. National governments must take a fundamental role in ensuring a stable and consistent investment channel that aligns regulations and innovations with a green trajectory addressing climate change. As Mazzucato writes: "**The Green New Deal refers to the transformation of production, distribution, and consumption across the entire economy. It must be supported by long-term, careful financing capable of assuming risks and mobilizing diverse investors**" [7]. The green transformation itself primarily involves achieving a cross-sectoral innovation approach aimed at building a diversity of projects within the mission.

True solutions to the climate crisis are our greatest hope for building a fairer and more enlightened economic system that eliminates deep inequalities and transforms the public sphere by strictly controlling corporate power, emphasizes Naomi Klein, adding: "**…the scientifically proven reality of climate change must occupy a central place in the progressive narrative on the dangers of unlimited greed and the need for genuine alternatives**" [5]. Global warming has radically progressive consequences: "**…the collective survival of humanity depends on the immediate halting of** (**the ruling social structure** - added D.E.)" [8].

Cathedral Thinking of the Entrepreneurial State

"We are on the brink of mass extinction, and you are only talking about money and telling us fairy tales about eternal economic growth."

Greta Thunberg [9]

Although neoliberal proponents claim that democracy and economic development through free markets mutually reinforce each other - **"The market supports democracy, just as democracy should normally strengthen the market**," asserts British journalist Martin Wolf - market mechanisms and democracy exclude one another. Democracy operates on the principle of "one person, one vote," whereas the market functions on the principle of "one dollar, one vote." Since democracy assigns equal weight to every individual regardless of wealth, it often undermines market logic.

Following Žižek's assertion that liberal-democratic institutional mechanisms are insufficient to regain control over capital - **"…there is a growing gap between the liberal-democratic institutions of parliamentary democracy and the logic of global financial capital, which increasingly escapes any form of democratic control…**" [10] - Mariana Mazzucato would agree. In her book *The Entrepreneurial State*, she warns that the problems facing neoliberal capitalist states today stem from forty years of weakening national governments' ability to manage economic, public, and industrial policies, driven by the neoliberal paradigm of market supremacy and the push for deregulation, which has marginalized government roles. Thus, "**…those who run global corporations…seek to manage the world as a single economic entity**" [11]. Hence, the need arises anew for "**…proper and effective management of social development**" [12].

The sluggish pace of the green transition demonstrates what happens when national governments leave urgent problems to the market and refrain from assuming their entrepreneurial role in society. Therefore, Giddens emphasizes that highly developed states must lead the way in turning "**…toward a low-carbon economy and introducing social reforms, in line with climate change. If they cannot do it, no one will**" [4].

Highly developed states must take the lead in reducing harmful gas emissions by shifting to a low-carbon economy and technologies, as well as in implementing necessary social reforms grounded in the concept of climate change. The state should encourage the creation of a creative environment that supports the diversity of social groups capable of developing long-term climate policies. Thus, the vision of the future arises through the synergy of economic, social, and political thinking: "**…as a response to climate change…we can expect a large**

number of technological innovations, and we should do everything to encourage them. Without such innovations, it is impossible to envision the end of our dependence on oil, natural gas, and coal, which are the primary sources of environmental pollution" [4].

In her address to the European Parliament (April 16, 2019), Greta Thunberg stressed that combating climate change requires a far-reaching vision and determined action. "Cathedral thinking" is needed. In the twenty-first century, "cathedrals" must be built through innovations that incorporate equality, justice, and sustainability. A different type of private sector is required - one with which governments can interact. This entails restoring the public interest in economic policies so that they primarily aim to generate benefits for citizens and establish goals that matter to people, driven by concern for the common good rather than profit alone. The public interest must be central to corporate governance, taking into account the needs of all stakeholders. Governments, therefore, should not merely repair markets but create them, investing in capacity building, promoting industrial production, fostering public-private partnerships, and supporting research, development, and education.

An avant-garde of entrepreneurs is necessary to provide new ventures and technologies based on a vision of a low-carbon future.

Recycled Capitalism

"It is easier to imagine the end of the world than the end of capitalism."

Mark Fisher [13]

Andreas Malm argues that the response to the global catastrophe is possible only within the capitalist state, since a workers' state will not be created overnight: **"It does not seem realistic that the dual power of democratic proletarian institutions will be realized anytime soon, or if ever. Waiting for this to happen would be both illusory and criminal, and therefore we must work within the grim bourgeois state, which, as always, is bound by the hands of capital**" [14].

Although the application of technological innovations in the "green transition" appears highly optimistic, people still serve the economy rather than the other way around. The very meaning of frugal resource use and sustainable development essentially lies in the maximization of resource exploitation. The heaps of waste left behind by consumerist consumption are, in fact, already designed by the logic of capitalism: **"The idea of total recycling (in which even the last remnants are reused) represents the ultimate capitalist dream. Even - or especially - when presented to preserve the Earth's natural balance. Another testament to capitalism's ability to appropriate ideologies that oppose it**" [15].

Thus, technological fixes, purchasing green products, and organizing emissions markets postpone the transformation of the existing socio-economic reality. If technological innovations are aimed at maximizing profit, it is unlikely that they will contribute meaningfully to solving global climate change. In fact, the use of 'benign' technologies will allow humanity to continue down the same path that has led to civilizational decline. Žižek warns that the fundamental mistake of Marx was his conclusion that a new, higher social order was possible, one that would not only preserve but also elevate and fully unleash the potential of the self-reinforcing spiral of productivity which, in capitalism, due to its inherent contradiction, repeatedly subverted society through destructive economic crises [16].

Therefore, Naomi Klein argues, a genuine transformation in the way the world is organized is required, a profound change in the fundamental principles of the economic system: "**…a serious discussion of the glaringly obvious roots of the climate crisis: globalization, deregulation, and the contemporary capitalist need for constant growth**" [17]. Žižek also maintains that changing the capitalist system is necessary to truly effect change: **"…we must accept that nothing can be changed within the existing system…true change is not merely the overthrow of the old order, but, above all, the establishment of a new one**" [3].

RESULTS AND DISCUSSION

Despite the urgent need for immediate action on climate change, green campaigns remain largely isolated, lacking a unified, globally coordinated strategy. Similarly, the innovative technological sector is primarily profit-driven, without a clear green vision. The unification of humanity in a global environmental protection movement, a broader international initiative, or a Green New Deal, is currently not on the horizon.

CONCLUSION

"It seems that the impending ecological crisis provides a unique opportunity for the acceptance of a reconfigured version of the dictatorship of the proletariat."

Slavoj Žižek [3]

The global system is not functioning. Numerous trends signal a deeply advanced disintegration of capitalism. Slavoj Žižek emphasizes that Marxism was correct regarding the "final crisis" of capitalism. According to Žižek, changes are already underway: **"…in broad daylight: capitalism openly disintegrates and transforms into something else. We do not perceive this ongoing transformation because we are immersed in ideology**" [3].
As Marv Waterstone points out, there exists a domain of concepts and categories within which the "common sense" of the masses is articulated: **"It is a pre-formed and self-evident field on which coherent ideologies and philosophies must compete for dominance, a foundation that new conceptions of the world must take into account, on which they must compete and transform if they wish to shape the masses' worldview and thereby become effective**" [18].
However, the supreme irony, Žižek argues, is that ideologies present themselves as their radical opposites, as radical critiques of ideological utopias: **"Every vision of another world is rejected as ideology**" [3]. Today, the dominant ideology is not a positive vision of a utopian future, but "**…cynical resignation, acceptance of what the 'world really is,' accompanied by the warning that even a slight change to the status quo leads to totalitarian chaos, Stalinism, and fascism**" [3]. Weak thought is at work, no longer striving in politics toward all-encompassing systems and global emancipatory projects. Alain Badiou, in this sense, stresses that the main function of ideological censorship is to crush hope, condemning any critical project as the opening of a path that ends in camps.
Žižek, in The Spirit of the Times, writes: **"Today, however, the prevailing cynical functioning of ideology merely asserts: 'You must be stupid to see it' - what? Hope for radical change**" [3].
Is there then any hope for radical social transformation?
To achieve social change, a space for alternative critique is necessary, one that relies on the difference between what is and what ought to be. Critical pedagogy and critical thinking. "Being" and "ought" are not necessarily the same thing: **"…although the dominant common sense striving to preserve the status quo attempts to equate them, to make things be equivalent to the way things ought to be, it closes off the possibility of any alternative change**" [18].
Louis Althusser further noted that ideology is not a symbolic order externally imposed on reality, but rather our engagement with reality. The reproduction of society in its totality, as well as the reproduction of the conditions of production, according to Althusser, encompasses the educational system, culture, science, consumer mentality, and gender discourses [19]. Thus, the task is to produce a symbolic fiction that will **"…intervene in reality and thereby cause changes within it**" [16]. However, we cannot simply rid ourselves of ideological lenses; "**…theoretical work is necessary**" [3]. As Lenin also stated: "**Without revolutionary theory, there can be no revolutionary movement**" [20].
Faced with bad news, it is easy to succumb to the temptation of cynical indifference, believing that collective action is doomed from the start and that hope for effective change was merely an illusion. Yet, to "**…truly change things, we must accept that nothing can**

be genuinely changed within the existing system" [3]. Hence, strategic urgency is required, the work of non-systemic thinking that offers something new to transcend the domination of global capitalism. A massive reconstruction of social mechanisms is necessary to confront the damage wrought by capitalism. According to Félix Guattari, reforms will not come from the "top" through laws, decrees, or bureaucratic programs, but through the promotion of innovative practices, the emergence of alternative experiences focused on respecting singularity and autonomous creative subjectivity, appropriately connected to the rest of society [21].

REFERENCES

[1] Badiou, Alain (2016). *Our Misery Comes from Afar – Our Evil Reaches Far*. Novi Sad: Akademska knjiga.
[2] Horkheimer, Max (1989). *Eclipse of Reason*. Sarajevo: Logos.
[3] Žižek, Slavoj (2019). *Like a Thief in Broad Daylight*. Belgrade: Laguna.
[4] Giddens, Anthony (2010). *Climate Change and Politics*. Belgrade: Clio.
[5] Klein, Naomi (2022). *The World in Flames*. Belgrade: FMK.
[6] Klein, Naomi (2015). *Only Radical Solutions Remain*, https://standard.rs/2015/02/16/naomi-klajn-ostala-su-nam-samo-radikalna-resenja/
[7] Mazzucato, Mariana (2022). *The Economy with a Mission*. Novi Sad: Akademska knjiga.
[8] Klein, Naomi (2018). *It Is Not Enough to Say No*. Belgrade: SamizdatB92.
[9] Gessen, Masha (2019). *Greta Thunberg as Anti-Trump*, https://pescanik-net.webpkgcache.com/doc/-/s/pescanik.net/greta-tunberg-kao-anti-tramp
[10] Žižek, Slavoj (2014). *Alternative to Capitalism*, https://pescanik.net/alternativa-kapitalizmu
[11] Barnet, R. & Mueller, R.E. (1974). *Global Reach: The Power of the Multinational Corporations*. New York: Simon and Schuster.
[12] Milačić, S. & Kostić, A. (2022). *Problems of Socio-Economic Development under Contemporary Globalization*, Economic Outlook/Ekonomski pogledi, 20(2).
[13] Fisher, Mark (2022). *Capitalist Realism: Is There an Alternative*. Belgrade: FMK.
[14] Malm, Andreas (2022). *Corona, Climate, Capitalism*. Belgrade: FMK.
[15] Žižek, Slavoj (2024). *We Are All Biomass*, https://pescanik.net/svi-smo-mi-biomasa/
[16] Žižek, Slavoj (2011). *In Defense of Lost Causes*. Novi Sad: Akademska knjiga.
[17] Klein, Naomi (2011). *Capitalism vs The Climate*, https://www.thenation.com/article/archive/capitalism-vs-climate/
[18] Chomsky, Noam & Waterstone, Marv (2022). *Consequences of Capitalism*. Novi Sad: Akademska knjiga.
[19] Althusser, Louis (2009). *Ideology and State Ideological Apparatuses*. Loznica: Karpos.
[20] Lenin, V.I. (1949). *What Is to Be Done*. Belgrade: Kultura.
[21] Guattari, Felix (2021). *The Three Ecologies*. Belgrade: FMK.

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A GREEN MODEL FOR BUSINESS IMPROVEMENT

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Abstract: The paper investigates the possibilities of improving the competitiveness of domestic companies through the integration of the concepts of sustainable development, knowledge and innovation. Starting from a theoretical literature review, a green model of business improvement was developed that connects the ecological, social and economic dimensions of sustainable development. The model shows how the rational use of resources, the implementation of clean technologies and the raising of environmental awareness can become a source of innovation and stable market positions, while continuous learning and development of employees strengthen the productivity and competitive position of the company. The paper provides guidelines for the introduction of socially responsible and long-term sustainable business, highlighting the importance of education, innovation and strategic management of resources. Although the model is based on theoretical insights, its practical application opens up space for empirical verification and adaptation to the specifics of the domestic economy.
Key words: green model, sustainable development, competitiveness, innovation, knowledge, socially responsible business

INTRODUCTION

The domestic economy in the new development phase should create and maintain a competitive advantage through entrepreneurship and enterprise innovation, in accordance with the concepts of sustainable development important for business and the environment [1, 2]. Raising the level of knowledge and accelerated technological development increase economic and technical opportunities, and this topic is significant because it is necessary to emphasize the management and management of business and market development through learning and application of knowledge as a factor of productivity and sustainability [3]. It is important to know that the application of the concept of sustainable development integrated with the knowledge and learning of organizations represents socially responsible business with a large number of positive effects [4, 5].
Sustainable development and economic progress of domestic companies requires the need to develop a competitive economy based on knowledge, new technologies and innovation. Managers must be effective together with all employees of the company. In an organization based on knowledge, quality and innovation, the productivity of each individual employee makes the entire system productive and sustainable [6]. Sustainable development, with its goals and vision, is established again and again in specific situations between different groups. That is why the education and information of managers and employees and the creation of their environmental awareness is a very important factor in establishing economic sustainability [7].
Domestic companies need a culture of business and education that will help to understand and establish sustainable development. Every company must first properly understand the long-term importance of sustainable development and socially responsible business. In order to successfully implement the dimensions of sustainable development, a company must effectively analyze and manage the dimensions. Therefore, domestic companies and their sustainable operations require coordination of sustainable development dimensions and support in the implementation of their policies. Also, it is necessary to remove the deficiencies in the implementation of aspects of sustainable development and to encourage companies to operate in a socially responsible and long-term sustainable manner [8, 9].

This paper aims to investigate and theoretically present the aspects of sustainable development and competitiveness of enterprises and, based on theoretical insights, to develop a green business model applicable in the domestic economy. The goal of developing the model is to adopt the concepts of sustainable development in business and highlight the advantages that sustainable business processes bring to companies.

METHODOLOGY

The problem and the subject of research

In modern business conditions, domestic companies face the challenge of how to simultaneously develop a competitive advantage and ensure long-term sustainability. However, many organizations still do not have a sufficiently developed culture of learning, environmental awareness and corporate social responsibility, which makes it difficult to integrate sustainable development concepts into growth and competitiveness strategies. Rapid technological progress, knowledge growth and the need for innovation require management to align business goals with the principles of sustainable development.
The subject of the research is a theoretical analysis and consideration of how the concepts of sustainable development can be integrated into the business processes of domestic companies in order to strengthen their competitive advantage, as well as the development of a green business model that can serve as a framework for long-term socially responsible and productive functioning of the domestic economy.

Research goal

The goal of the research is to develop a green business model, based on theoretical insights, that connects the principles of sustainable development with strategies to increase the competitiveness of domestic companies.

Research question

Based on analyzed theories, we will try to answer the following question:

- How can the application of sustainable development concepts, relying on knowledge and innovation, contribute to creating and preserving the competitive advantage of domestic companies?

Research method

This is a form of theoretical research in which conclusions are made by considering previous conducted research, studies and literature.

RESULTS AND DISCUSSION

Literature review

Sustainable development of the company, i.e. corporate sustainability, is defined as a business approach focused on creating long-term value for the company, through consideration of all dimensions of the relationship to its economic, social and natural environment [10]. Creating an ecological, "green strategy" focused on the environment and including all aspects of environmental responsibility is considered an extremely important step towards sustainable development [11, 12]. The essence of the sustainable development of the company is in the economical and rational use of resources, and sustainable development enables an increase in the quality of life according to ecological possibilities. The concept of sustainable development represents a combination of scientific principles and human values, that is, it

implies a redetermination of rules in order to replace wasteful consumption with savings and conservation [13, 14].
When it comes to the strategy of sustainable development, the national economic development strategy of the Republic of Serbia recognizes three pillars of sustainable development, i.e. environmental, social and economic. In the part of the strategy that deals with the economic dimension of sustainable development, the basic assumptions based on knowledge as the most important resource, when it comes to the economy, are defined. Goals such as sustainable production and consumption, education and similar areas within the economic dimension are defined. In the part of the strategy that deals with the social dimension of sustainable development, social values, the well-being of society, gender equality, poverty and similar indicators were analyzed. The part of the strategy that includes the ecological dimension of sustainable development deals with the protection of natural resources, such as air, water, soil, forests etc [15].
Competitiveness represents a series of institutions, policies and factors that determine the level of productivity of a country. The clearest manifestation of competitiveness is reflected in labor productivity and its level, which enables long-term sustainability of economic growth and development. Competitiveness is determined by the level of productivity with which a country uses resources, such as natural resources, human resources and capital, which is why it is a key factor that determines the well-being of the country and its citizens. Serbia, as a European country that aspires to reach a medium and high income level, should develop and implement a competitiveness strategy based on innovation. An economy driven by innovation creates a competitive position on the global market by constantly innovating products and services as a key factor of competitive advantage. Such an economy in a modern business environment uses the possibilities of modern technology in order to maintain competitive ability in the long term [16].
Improving the competitiveness of the economy implies successfully solving the entire complex of long-term tasks. The basis of the concept of long-term successful socio-economic development needs to be based on the project of reforming the economy, the content of which consists of four interconnected complexes, namely institutions, infrastructure, investments and innovations [17]. Without adequate and continuous application of knowledge in the process of managing the organization, there is neither economic development nor the establishment of the competitiveness of the national economy [18]. Therefore, education and knowledge are new factors of competitiveness. The most important course of action in the function of developing the competitiveness of domestic business organizations is more adequate use of knowledge in organizations. The task of education in the field of management techniques and skills is to acquire knowledge that is necessary to successfully manage business and enterprise, with the aim of increasing the productivity of both work and knowledge [19].
The importance of quality and innovation, both in business and in the entire economy, are closely related. Innovation means the ability of an economy, company or individual to translate new business ideas into new products, services, technologies, markets. The basic meaning of innovation is the process of arriving at new products and services in a more efficient way compared to the earlier period. Domestic companies on the territory of the entire Serbian market must adopt strategies based on innovation and knowledge. New and successful multinational companies with plans to create innovative products are investing in the global business scene, as are new innovative companies from developing countries.

Development of a green model for business improvement

Based on the review of existing literature, that is, theoretical research, a green business improvement model was created that can be applied in the domestic economy, and which is based on the principles of sustainability, quality improvement and competitiveness. The model is presented in Figure 1.

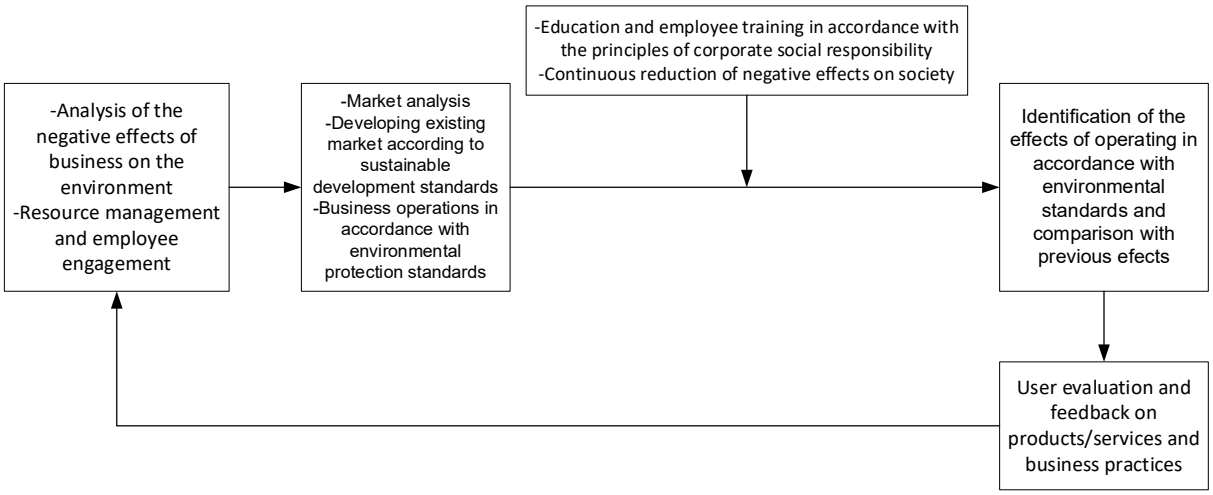


Fig. 1. *A green model for business improvement*

The presented model is based on the assumption that companies can simultaneously build competitive advantage and long-term sustainability, which represents the integration of three dimensions of sustainable development, i.e. ecological, social and economic. The ecological dimension supported by the model includes the rational use of resources and the reduction of negative impact on the environment, through the introduction of green strategies in business processes. The social dimension implies the development of an organizational culture that encourages socially responsible business, employee education and raising environmental awareness, and the economic dimension implies the strengthening of productivity through continuous learning, innovation and the application of knowledge in business practices. Therefore, the created model shows the synergy of the mentioned dimensions of sustainable development because environmental goals become a source of innovation and new market opportunities, while social responsibility and education create a resilient and motivated workforce.

When it comes to practical applicability, the model provides a framework that domestic companies can use as guidelines for introducing green business strategies into their internal processes, training managers and employees to manage knowledge and innovation and increase productivity in the long term while preserving natural resources and caring for the wider community. The developed model represents an opportunity to strengthen the company's market position and implement cleaner technologies.

As a limitation of the model, the fact that it is based exclusively on theoretical analysis can be pointed out, which means that it should be empirically verified through certain case studies in domestic companies, in order to practically confirm its relevance. Further work could include measuring implementation effects, such as productivity indicators, emissions reductions and market share growth, as well as identifying barriers in practice, such as lack of financial resources or insufficiently developed awareness of the importance of sustainable development.

GUIDELINES AND RECOMMENDATIONS

Based on the research and model presented in this paper, the following guidelines and recommendations are offered:

- Companies should integrate the three dimensions of sustainability into their business strategy, i.e. develop the environmental, social and economic dimensions in order to achieve a competitive advantage and stable growth.
- Companies should continuously invest in employee education and the creation of internal processes that encourage innovation, because knowledge and innovation are the main drivers of productivity and competitiveness.

- Implementation of clean technologies, rational use of resources and reduction of negative impact on the environment should become an integral part of business plans of companies and new market opportunities.
- Management should continuously work on educating and motivating employees for socially responsible business and the preservation of natural resources.
- The state should participate in the creation of a sustainable economy through various incentives and regulatory frameworks, in order to provide support to businesses in sustainable transformation.

CONCLUSION

The results of theoretical research indicate that domestic companies can simultaneously build competitive advantage and long-term sustainability through the integration of three dimensions of sustainable development. The green model developed in this paper shows how environmental goals, through rational use of resources and reduction of negative impact on the environment, become a source of innovation and new market opportunities. At the same time, social responsibility and employee education create a resilient and motivated workforce, while the economic dimension, through continuous learning, innovation and application of knowledge, directly strengthens productivity and competitiveness. In this way, the application of sustainable development concepts, with reliance on knowledge and innovation, contributes to the creation and preservation of the competitive advantage of domestic companies (RQ:1). The proposed model can serve as a practical framework for managers and decision makers, as it highlights the need for continuous investment in education and innovation, as well as for the implementation of clean technologies that reduce risks and costs in the long term. Although the model is theoretically based and needs to be empirically verified in practice, it provides guidelines that can encourage domestic enterprises to improve sustainability and competitiveness strategies. In this way, it opens up the possibility to improve the economic position of the company and to contribute to wider social and environmental progress.

REFERENCES

[1] N. A. Alkathiri, F. B. Said, N. Meyer, and M. Soliman, "Knowledge management and sustainable entrepreneurship: a bibliometric overview and research agenda," *Journal of Innovation and Entrepreneurship*, Vol. 13, No. 1, 2024, doi: 10.1186/s13731-024-00387-3

[2] M. Leal, C. Leal, and R. Silva, "Entrepreneurial Ecosystems and Knowledge Management: Systematic literature review and bibliometric analysis," *Journal of the Knowledge Economy*, Apr. 2025. doi: 10.1007/s13132-025-02730-9

[3] S. Wang, J. Abbas, M. S. Sial, S. Álvarez-Otero, and L.-I. Cioca, "Achieving green innovation and sustainable development goals through green knowledge management: Moderating role of organizational green culture," *Journal of Innovation & Knowledge*, Vol. 7, No. 4, p. 100272, 2022. doi: 10.1016/j.jik.2022.100272

[4] W. Karar, A. Alzubi, A. Khadem, and K. Iyiola, "The nexus of sustainability innovation, knowledge application, and entrepreneurial success: Exploring the role of environmental Awareness," *Sustainability*, Vol. 17, No. 2, pp. 716, 2025. doi: 10.3390/su17020716

[5] Q. Yu, S. Aslam, M. Murad, W. Jiatong, and N. Syed, "The impact of knowledge management process and intellectual capital on entrepreneurial orientation and innovation," *Frontiers in Psychology*, Vol. 13, 2022. doi: 10.3389/fpsyg.2022.772668

[6] N. Yusof, A. A. Tabassi, and E. M. Kamal, "Do environmental, economic and reputational advantages strengthen green practices' impact on environmental performance?," *Corporate Social Responsibility and Environmental Management*, Vol. 27, No. 5, pp. 2081–2093, 2020. doi: 10.1002/csr.1948

[7] N. Mulaessa and L. Lin, "How do proactive environmental strategies affect green innovation? the moderating role of environmental regulations and firm performance," *International Journal of Environmental Research and Public Health*, Vol. 18, No. 17, p. 9083, 2021. doi: 10.3390/ijerph18179083
[8] M. B. M. Ladičorbić *et al.*, "Corporate Social Responsibility (CSR) in a transitional country context," *DETUROPE - the Central European Journal of Tourism and Regional Development*, Vol. 16, No. 1, pp. 43–74, 2024. doi: 10.32725/det.2024.003
[9] B. Melovic, N. Milovic, T. Backovic-Vulic, B. Dudic, and P. Bajzik, "Attitudes and Perceptions of Employees toward Corporate Social Responsibility in Western Balkan Countries: Importance and Relevance for Sustainable Development," *Sustainability*, Vol. 11, No. 23, p. 6763, 2019. doi: 10.3390/su11236763
[10] E. Nogueira, S. Gomes, and J. M. Lopes, "Unveiling triple bottom line's influence on business performance," *Discover Sustainability*, Vol. 6, No. 1, 2025. doi: 10.1007/s43621-025-00804-x
[11] A. Sulich and L. M. Sołoducho-Pelc, "Sustainable development in production companies: integrating environmental strategy and green management style," *Discover Sustainability*, Vol. 6, No. 1, 2025. doi: 10.1007/s43621-025-01152-6
[12] Q. Wang and G. Li, "Research on the Effect of Corporate environmental responsibility on corporate sustainability and the Mediator Effect of Corporate Environmental Strategy," *SAGE Open*, Vol. 14, No. 3, 2024. doi: 10.1177/21582440241266115
[13] S. E. Shmelev and E. Gilardi, "Corporate Environmental, social, and governance performance: the impacts on financial returns, business model innovation, and social transformation," *Sustainability*, Vol. 17, No. 3, p. 1286, 2025. doi: 10.3390/su17031286
[14] A. Marfu *et al.*, "Building Long-Term Value: A Practical Guide to Integrating ESG into Business Strategies," *Sustainable Futures*, p. 100955, 2025. doi: 10.1016/j.sftr.2025.100955
[15] J. Pivasevic and P. Hafner, "Institutional dimension of sustainable development," *Skola Biznisa*, No. 3–4, pp. 119–128, 2013. doi: 10.5937/skolbiz1304119p
[16] S. Đuričin, I. Beraha, O. Jovanović, M. M. Ružičić, M. Lazarević-Moravčević, and M. Paunović, "The efficiency of national innovation policy programs: the case of Serbia," *Sustainability*, Vol. 14, No. 14, p. 8483, 2022. doi: 10.3390/su14148483
[17] A. Canatay, L. Prieto, and M. R. Amin, "Navigating the convergence of global Competitiveness and Sustainable Development: A Multi-Level analysis," *Sustainability*, Vol. 17, No. 12, p. 5361, 2025. doi: 10.3390/su17125361
[18] S. S. Awode and M. O. Oduola, "The interplay between technological innovation and human capital development in driving industrial productivity and competitiveness in Africa," *Journal of Economics and Development*, 2024. doi: 10.1108/jed-03-2024-0079
[19] M. R. Uddin, N. Sadik, and Md. M. Rahman, "Globalization, physical capital, and human capital nexus with economic growth: evidence from BIMSTEC," *Research in Globalization*, p. 100284, 2025. doi: 10.1016/j.resglo.2025.100284

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CHEMICAL POLLUTANTS IN SOIL IN VRNJAČKA BANJA

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Abstract: This report presents a comprehensive analysis of soil chemical pollutants in the municipality of Vrnjačka Banja, Serbia, based on a recent soil quality report. The primary objective was to characterize the geochemical composition of soil from various land-use types, including agricultural, recreational, roadside, and a site adjacent to a landfill. The study method involved the analysis of five soil samples for a suite of parameters, including heavy metals, organic matter content, and physical properties. The measured concentrations were systematically compared against national Serbian regulations and recommendations for future actions were given.
Key words: soil, chemical pollutants, environment

INTRODUCTION

Global context of soil pollution

Soil is a finite and indispensable resource that forms the foundation of terrestrial ecosystems, providing a multitude of vital functions and ecosystem services. It is the primary medium for food and biomass production, a critical component of the water cycle responsible for filtration and purification, and a significant reservoir for carbon and nitrogen. [1] Globally, however, this essential resource is under increasing threat from a wide range of degradation processes, including erosion, loss of organic matter, compaction, and, most critically, pollution. Soil contamination, stemming from both point source and diffuse pollution, represents a major challenge to human health, food security, and environmental stability. Anthropogenic activities such as industrial production, intensive agriculture, transportation, and waste disposal introduce a diverse array of chemical pollutants into the soil matrix. These contaminants, which include heavy metals and persistent organic pollutants, can compromise soil fertility, enter the food chain, and leach into groundwater, posing long-term risks to both human and ecological systems. Addressing this complex issue requires a holistic and multi-faceted approach, encompassing comprehensive monitoring, robust regulatory frameworks, and targeted remediation strategies.

The study area: Vrnjačka Banja

Vrnjačka Banja is a health resort located in the central part of the Republic of Serbia, situated at 43° 37' North latitude and 20° 54' East longitude. The town's unique geographical setting lies partly on the gentle slopes of Mount Goč and partly within the valleys of the Lipovačka and Vrnjačka rivers, which flow towards the Zapadna Morava River. The region's temperate continental climate and abundant thermal-mineral springs have established it as one of Serbia's most renowned and popular spa towns. However, Vrnjačka Banja is also a modern municipality with diverse land-use patterns, including agricultural areas, recreational zones, major roadways, and waste disposal sites.

Research rationale and objectives

The aim of this study is to provide a comprehensive analysis of soil quality in the Vrnjačka Banja municipality by evaluating the concentration of various chemical pollutants.

Pollutants of concern and their environmental fate

The analysis of soil quality in this study focuses on two primary categories of chemical pollutants: heavy metals and organic compounds. Heavy metals, such as copper (Cu), zinc (Zn), lead (Pb), chromium (Cr), nickel (Ni), cobalt (Co), and cadmium (Cd), are naturally occurring elements that become environmental contaminants when their concentrations are elevated by human activities. Common anthropogenic sources include industrial emissions, vehicle exhaust (historically from leaded gasoline), and agricultural inputs such as fertilizers and animal manure, which can contain high concentrations of Cu and Zn. Once deposited, the environmental fate and bioavailability of these metals are strongly influenced by soil characteristics, particularly pH, organic matter content, and clay percentage. Generally, a higher pH and increased organic and clay content promote the sorption of heavy metals, reducing their mobility and potential for leaching or plant uptake.

Organic pollutants, specifically Polycyclic Aromatic Hydrocarbons (PAHs) and mineral oil hydrocarbons, are also of significant concern. PAHs are a group of chemical compounds formed during the incomplete combustion of organic materials such as coal, oil, gas, wood, and garbage. Sources include industrial emissions, vehicle exhaust, and waste incineration. [2] Similarly, mineral oil hydrocarbons are found in crude oil and refined petroleum products, and their presence in soil is typically the result of accidental spills from industries, transportation, or unmanaged waste. These compounds are highly hydrophobic, meaning they have a strong affinity for soil organic matter. This characteristic causes them to bind tightly to soil particles, limiting their mobility but also contributing to their long-term persistence in the environment. The degradation of these compounds is primarily mediated by microbial metabolism, a process that can be supported by phytoremediation techniques.

Geogenic sources of heavy metals in Serbia

A critical factor in the interpretation of soil heavy metal concentrations in Serbia is the country's unique geological background. Numerous studies have established that certain regions, particularly in central and western Serbia, are underlain by ultramafic rocks, commonly referred to as serpentinites. These parent rocks are naturally enriched with specific trace elements, including nickel (Ni), chromium (Cr), and cobalt (Co). [3]
The presence of these geogenic sources means that background concentrations of Ni and Cr can be significantly higher in these soils compared to typical values found in other parts of Europe.

Serbian regulatory frameworks

The Republic of Serbia has established a legal framework for environmental protection, with a specific focus on soil quality. This regulation defines Maximum Allowed Quantities (MDK) for a list of hazardous and harmful substances. [4,5]
The Serbian legal framework also includes a provision for systematic soil quality monitoring and emphasizes the "polluter pays" principle, placing the responsibility for remediation on the party that caused the pollution.

MATERIAL AND METHODS

Sample locations

Five soil samples were collected from different land-use types within the Vrnjačka Banja municipality. Each sample was taken from a depth of 0-30 cm, representing the topsoil layer most susceptible to contamination. The sampling sites were chosen to represent a cross-section of land uses in the region. The locations, along with their geographical coordinates and land-use classifications, are as follows:

- Sample ID A: Agricultural land located at 43° 39' 53.6" N, 20° 54' 53" E.
- Sample ID B: Recreational zones 1 located at 43° 37' 03.7" N, 20° 53' 39.2" E.
- Sample ID C: Main traffic road located at 43° 38' 17.2" N, 20° 55' 01.3" E.
- Sample ID D: Recreational zone 2 located at 43° 36' 36.7" N, 20° 53' 38.3" E.
- Sample ID E: Near a landfill located at 43° 40' 39.5" N, 20° 51' 29.1" E.

Techniques of UV/VIS spectrophotometry, AAS-F, AAS-ES, direct analysis technique Hg (DMA), ICP-MS, ICP-OES were applied for the analysis of sediment samples.

Analytical parameters

The soil samples were analyzed for a comprehensive suite of physical, chemical, and pollutant parameters. These parameters can be grouped into the following categories:

- **Physical/Chemical Properties:** Organic matter content, Coarse sand, Silt, Moisture content, pH in KCl and pH in H_2O.
- **Heavy Metals and Other Elements:** Copper (Cu), Zink (Zn), Cobalt (Co), Lead (Pb), Cadmium (Cd), Nickel (Ni), Chromium (Cr), Arsenic (As), Mercury (Hg), Antimony (Sb), Barium (Ba), and Beryllium (Be).
- **Organic Pollutants:** Toluene, Xylene, Ethylbenzene, Styrene, Anthracene, Benzene, total Polychlorinated Biphenyls (PCBs), and total Polycyclic Aromatic Hydrocarbons (PAHs), along with the sum of C10-C40 mineral oil hydrocarbons.

RESULTS AND DISCUSSION

The analysis of the five soil samples from Vrnjačka Banja provides a detailed profile of their physical, chemical, and pollutant characteristics. The results are presented in a series of tables to facilitate a direct comparison and assessment.

Table 1. *Physical and Chemical Properties of Vrnjačka Banja Soils*

Sample ID	Location type	Organic matter (%)	Coarse sand (%)	Silt (%)	Water content (%)	pH (KCl)	pH (H_2O)
A	Agricultural land	18.04	6.8	84.9	2.99	6.01	6.9
B	Recreational zones 1	7.92	22.4	69.4	2.42	6.97	7.55
C	Main traffic road	5.03	24.3	74.4	1.37	7.11	7.66
D	Recreational zones 2	6.59	40.7	48.2	1.97	7.19	7.86
E	Near a landfill	5.99	34.0	62.8	3.15	7.55	8.07

As shown in Table 1, the sampled soils exhibit a range of physical and chemical properties. The agricultural land sample is distinguished by a significantly higher organic matter content (18.04%) and a more acidic pH (pH(KCl)=6.01, pH(H_2O)=6.9) compared to the other sites. In contrast, the other four locations have lower organic matter content (5.03% to 7.92%) and are more neutral to alkaline (pH(KCl)=6.97−7.55, pH(H_2O)=7.55−8.07). The texture of the soil varies, with the agricultural and recreational sites having a high silt content, while the second recreational site has a higher coarse sand percentage. [6]

Table 2. *Concentration of Heavy Metals in Vrnjačka Banja Soils*

Pollutant (mg/kg dry matter)	Agricultural land	Recreational zones 1	Main traffic road	Recreational zones 2	Near a landfill	Serbian MDK
Cu	31.86	23.4	23.25	19.66	31.39	100
Zn	87.73	86.0	89.25	75.0	130.05	300
Co	24.32	26.7	19.25	20.72	23.08	N/A
Pb	26.82	37.71	49.0	40.86	84.61	100
Cd	<0.8	<0.8	<0.8	<0.8	<0.8	3
Ni	239.32	304.21	182.5	267.55	296.39	50
Cr	174.09	368.28	224.5	266.83	194.23	100
As	11.1	14.23	14.07	12.25	22.97	25
Hg	<0.25	<0.25	<0.25	<0.25	0.41	2
Sb	<0.5	<0.5	<0.5	<0.5	<0.5	N/A
Ba	43.73	58.2	58.95	13.22	49.71	N/A
Be	<0.5	<0.5	<0.5	<0.5	<0.5	N/A

The results in Table 2 highlight a key finding: a significant discrepancy between the measured concentrations of nickel (Ni) and chromium (Cr) and the Serbian regulatory limits. All five samples show Ni concentrations ranging from 182.5 mg/kg to 304.21 mg/kg, and Cr concentrations from 174.09 mg/kg to 368.28 mg/kg. These values are consistently 3 to 6 times higher than the Serbian MDKs of 50 mg/kg for Ni and 100 mg/kg for Cr. Conversely, other heavy metals show concentrations well below their respective MDKs. For instance, lead (Pb) concentrations range from 26.82 mg/kg to 84.61 mg/kg, remaining below the 100 mg/kg limit. Zinc (Zn), Copper (Cu), and Arsenic (As) are also well within their permissible limits, with the highest concentration for all three found at the agricultural and landfill-adjacent sites. Cadmium (Cd) and mercury (Hg) are below detection limits for most samples, except for a trace amount of Hg at the landfill-adjacent site. [6]

Table 3. *Concentration of Organic Pollutants in Vrnjačka Banja Soils*

Pollutant	Agricultural land	Recreational zones 1	Main traffic road	Recreational zones 2	Near a landfill
Toluene (mg/kg)	<0.002	<0.002	<0.002	<0.002	<0.002

Xylene (mg/kg)	<0.002	<0.002	<0.002	<0.002	<0.002
Styrene (mg/kg)	<0.002	<0.002	<0.002	<0.002	<0.002
Total PCB (mg/kg^2)	<0.01	<0.01	<0.01	<0.01	<0.01
Ethylbenzene (mg/kg)	<0.002	<0.002	<0.002	<0.002	<0.002
Anthracene (µg/kg)	<0.03	<0.03	<0.03	<0.03	<0.03
Benzene (µg/kg)	<0.03	<0.03	<0.03	<0.03	<0.03
Total PAH (µg/kg)	<0.03	<0.03	<0.03	<0.03	0.164
Total mineral oils (C10-C40) (mg/kg)	<1	<1	<1	<1	254

Table 3 reveals a distinct pattern for organic pollutants. For the majority of the samples (agricultural, recreational, and traffic-exposed), most organic compounds, including various PAHs, PCBs, and mineral oils, were found to be below the detection limits. This indicates that diffuse, widespread organic contamination is not a significant issue in the sampled areas. However, the sample taken near the landfill presents a clear exception. This site shows a total PAH concentration of 0.164 µg/kg and, more notably, a significant level of C10-C40 mineral oils at 254 mg/kg. This finding is consistent with the land-use classification and suggests a direct, localized source of contamination. [6]

Assessment of Soil Quality: A Dual Narrative

The analytical results from the Vrnjačka Banja soil samples paint a complex picture of soil quality, revealing a composition influenced by both the region's unique geological makeup and specific human activities. On a general level, the soil appears to be in good condition, with the most common contaminants, such as lead, cadmium, and various organic compounds, present at concentrations well below national regulatory limits or even below detection. The samples from the traffic road and recreational zones, for example, show no evidence of significant contamination from vehicle exhaust or other urban sources, such as Pb, PAHs, and mineral oils are all at very low or non-detectable levels. This is particularly noteworthy for the Main traffic road site, as traffic has historically been a major source of lead pollution from the use of leaded gasoline. The current low concentrations may reflect the effectiveness of past environmental policies and a low volume of heavy vehicle traffic on that specific roadway, contrasting with findings in more densely urbanized areas like Belgrade where Pb levels near traffic arteries were found to be significantly higher. [7,8]

However, the most striking finding is the consistently high concentration of nickel (Ni) and chromium (Cr) across all five samples. As presented in Table 2, these values universally exceed the Serbian regulatory MDKs. A superficial analysis would classify these soils as polluted and in need of remediation. A deeper investigation, however, requires a critical evaluation of the underlying geology. Research on Serbian and Balkan geology confirms that the region contains significant areas of ultramafic (serpentine) parent rocks that are naturally rich in Ni, Cr, and Co. The observed levels of Ni (182.5-304.21 mg/kg) and Cr (174.09-368.28 mg/kg) in Vrnjačka Banja soils, while high in a regulatory sense, are well within the range expected for an area influenced by this geogenic background. This suggests that the measured concentrations are not the result of human-caused pollution but are, in fact, a natural characteristic of the local soil. [9,10]

This situation underscores the need for a more nuanced regulatory approach that distinguishes between natural geochemical anomalies and genuine anthropogenic contamination.

Analysis of Anthropogenic Pollutants

While the heavy metal profile is dominated by a geogenic signature, the analysis of organic pollutants reveals a clear and direct link to a specific anthropogenic activity. The four samples representing agricultural, recreational, and traffic-exposed land uses show virtually no detectable levels of PAHs or mineral oils. This indicates a general absence of widespread organic contamination in the Vrnjačka Banja area.

The sole exception is the sample from the location "Near landfill". This site exhibits a total PAH concentration of 0.164 µg/kg and a substantial concentration of C10-C40 mineral oils at 254 mg/kg. This finding is a strong example of point-source pollution. While the measured PAH concentration is relatively low compared to industrial "hot spots" in Europe, where levels can reach thousands of µg/kg, it is a definitive signature of localized human impact. [11]

The presence of other heavy metals at the landfill-adjacent site also merits consideration. The concentrations of Cu (31.39 mg/kg) and Zn (130.05 mg/kg) are the highest among all samples, although still well below the Serbian MDKs. This is consistent with the literature, which identifies industrial waste and municipal garbage as sources of these metals. Furthermore, the sample from the agricultural site shows the highest levels of Cu (31.86 mg/kg) and Zn (87.73 mg/kg), which is likely due to the application of fertilizers and animal manure in farming practices. [12,13]

This observation demonstrates how different land uses create distinct pollution signatures, with agriculture contributing to elevated levels of essential micronutrients like Cu and Zn, while waste disposal creates localized organic contamination. The findings confirm that even in a region celebrated for its natural qualities, localized human activity can create distinct and measurable environmental impacts.

CONCLUSION

Summary of Findings

The geochemical assessment of soil in Vrnjačka Banja reveals a complex environmental profile shaped by both natural and human influences. The study's central finding is the pervasive presence of nickel (Ni) and chromium (Cr) at concentrations that significantly exceed Serbian regulatory thresholds. This phenomenon is not attributed to pollution but is a natural, geogenic characteristic of the region's soils, likely stemming from underlying ultramafic rocks. All other major heavy metals, including lead (Pb), cadmium (Cd), copper (Cu), and zinc (Zn), are well below their respective regulatory limits, suggesting a low level of widespread contamination. However, a distinct anthropogenic signature was identified at the site adjacent to a landfill, where measurable levels of polycyclic aromatic hydrocarbons (PAHs) and a substantial concentration of mineral oil hydrocarbons were detected. This localized organic pollution provides a clear example of point-source contamination linked to human activity. In summary, the soil of Vrnjačka Banja presents a dual narrative: one of a natural, geochemically rich environment with naturally high levels of certain elements, and another of a contemporary landscape with localized, human-induced environmental impacts.

Recommendations for Future Action

Based on the findings of this report, the following recommendations are proposed to guide future policy, monitoring, and research in Vrnjačka Banja and similar regions of Serbia:

- **Review and Modernize Regulatory Frameworks:** A critical review of the Serbian soil quality standards, particularly the Maximum Allowed Quantities for nickel and chromium, is necessary. The current single-value thresholds do not account for natural geogenic background levels, leading to the misclassification of natural soils as contaminated.

- **Implement Systematic Soil Monitoring:** A comprehensive, long-term soil quality monitoring program should be established for the municipality of Vrnjačka Banja, focusing on high-risk land-use categories such as agricultural zones, main traffic routes, and, most importantly, waste disposal sites. This monitoring should track both heavy metals and organic pollutants to identify changes over time and confirm that pollution prevention measures are effective.
- **Prioritize Risk-Based Management and Remediation:** Given the confirmed point-source contamination at the landfill-adjacent site, immediate action should be taken to assess the risk posed by the detected PAHs and mineral oils.
- **Conduct Further Geochemical Research:** To fully understand the potential risks associated with naturally elevated heavy metal levels, further research is required. This should include speciation analysis of the Ni and Cr to determine their bioavailability and mobility in the soil. Furthermore, an expanded sampling program across the entire municipality would provide a more complete picture of the spatial distribution of contaminants and allow for the creation of a detailed geochemical map of the region. This research is crucial for a health resort like Vrnjačka Banja, where environmental quality is inextricably linked to its reputation and function as a therapeutic destination.

REFERENCES

[1] European Union, Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on Soil Monitoring and Resilience (Soil Monitoring Law), Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52023PC0416
[2] Internet source: National Library of Medicine, National Center for Biotechnology Information, Toxicological Profile for Polycyclic Aromatic Hydrocarbons, website: https://www.ncbi.nlm.nih.gov/books/NBK598178/
[3] Quantin, C., Ettler, V., Garnier, J., Šebek, O.: Sources and extractability of chromium and nickel in soil profiles developed on Czech serpentinites, Compte Rendus, Géoscience, Vol. 340, no. 12, pp. 872-882, 2008.
[4] Regulation on Allowed Quantities of Hazardous and Harmful Substances in Soil and Irrigation Water and Methods of Their Testing, Official Gazette of Republic of Serbia, no. 23/94. website: https://pravno-informacioni-sistem.rs/eli/rep/sgrs/ministarstva/pravilnik/1994/23/1/reg
[5] Regulation on Limit Values of Pollutants, Harmful and Dangerous Substances in Soil, Official Gazette of Republic of Serbia, no. 30/2018 and 64/2019, website: https://pravno-informacioni-sistem.rs/eli/rep/sgrs/vlada/uredba/2018/30/2/reg
[6] Internet source: Serbian Environmental Protection Agency (SEPA), website: https://sepa.gov.rs/zemljiste-2/
[7] Ivankovic, N., Kasanin-Grubin, M., Brceski, I., Vukelic, N.: Possible sources of heavy metals in urban soils: Examples from Belgrade, Serbia, Journal of Environmental Protection and Ecology, Vol. 11, no. 2, pp. 455-464, 2010.
[8] Tešić, M., Stojanović, N., Knežević, M., Đunisijević-Bojović D., Petrović, J., Pavlović, P.: The Impact of the Degree of Urbanization on Spatial Distribution, Sources and Levels of Heavy Metals Pollution in Urban Soils – A Case Study of the City of Belgrade (Serbia), Sustainability, Vol. 14, no. 20, 13126, 2022.
[9] Tošić Jojević, S., Mrvić, V., Stajković-Srbinović, O., Jovković, M., Antić Mladenović, S., Krpović, M., Belanović Simić, S.: Geochemical Distribution of Ni, Cr, and Co in the Main Soil Types of the Čemernica River Basin in Serbia (In a Serpentine Environment), Land, Vol. 13, no. 12, 2075, 2024.
[10] Vicić, D., Stoiljković, M., Ninkov, J., Bojat, N., Sabovljević, M., Stevanović B.: Dynamics of soil chemistry in different serpentine habitats from Serbia, Journal of the Serbian Chemical Society, Vol. 79, no. 9, pp. 1185-1198, 2014.

[11] Maliszewska-Kordybach, B.: Soil quality criteria for polycyclic aromatic hydrocarbons – Current information and problems, Fresenius environmental bulletin, Vol. 12, no. 8, pp. 919-924, 2003.
[12] Ballabio, C., Panagos, P., Lugato, E., Huang, JH., Orgiazzi, A., Jones, A., Fernández-Ugalde, O., Borrelli, P., Montanarella, L.: Copper distribution in European topsoils: An assessment based on LUCAS soil survey, Science of The Total Environment, Vol. 636, pp. 282-298, 2018.
[13] Agency for Toxic Substances and Disease Registry, Toxicological Profile for Zinc, 2005, Available at https://www.atsdr.cdc.gov/ToxProfiles/tp60.pdf

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ANALYTICAL SOLUTION OF SPATIAL DISTRIBUTION OF AIR POLLUTION FROM POINT SOURCES

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Abstract: This paper analyses the distribution of particulate air pollution originating from a specific location, modeled as a point source with periodic operation. The extent of the observed pollution is considered in one direction, accounting for diffusion and absorption processes in relation to current air flow conditions. The diffusion equation describing these processes is a partial differential equation and must ultimately be solved numerically for realistic parameters.
Key words: Periodic point source of pollution; particulate air pollution; diffusion-absorption processes; spatial distribution of pollution particles.

INTRODUCTION

The problem of environmental pollution is becoming acute due to rapid technical and technological development, especially in the air and particularly in large industrial centers.
Air pollution refers to the state of the atmosphere in which substances are present at concentrations above established normal values and are harmful to the environment and humans. This pollution results from natural phenomena and human activities and can therefore be divided into pollution from natural sources and pollution from anthropogenic sources [1].
Natural sources of air pollution have always existed in the biosphere and include: deflation—the transfer of soil and sand, usually in desert and forest-steppe zones; smoke from forest and steppe fires, which contains CO, soot, resin, tar, and other substances; volcanoes, as strong eruptions release large amounts of dust, gases, SO_2, CO_2, and more; mineral and thermal springs, which can emit CO_2, H_2S, methane, and similar gases; cosmic dust, especially if radioactive; large marine areas, which can release CO_2, CO, H_2S, chlorides, and other compounds; and natural disasters, such as storms and earthquakes, that are associated with significant emissions of air pollutants.
Anthropogenic sources of pollution can be classified as stationary or mobile sources. Mobile sources include motor vehicles with internal combustion engines. Indoor sources of air pollution include emissions from combustion and heating, as well as emissions from various materials or substances, such as the evaporation of organic compounds, various synthetic chemicals, and tobacco smoke.
Based on the number of sources and their spatial distribution, pollutants can be classified as individual, point (static or mobile), group (static or mobile), or linear. Depending on the type of emission, pollutant sources are divided into particle and gas emitters.
The greatest importance of understanding and predicting the spread of air pollution lies in its negative impact on human health. There is no direct link between the health of the population and the state of the environment, as various other factors also influence public health. However, the environmental factor, along with heredity and individual lifestyle characteristics, is important for the availability and effectiveness of health services. Air quality in urban areas is considered to have a greater impact on public health than other environmental factors, and outdoor air pollutants are among the most significant causes of health problems overall. Numerous epidemiological studies have clearly demonstrated that air pollution in the form of

irrespirable particles is associated with increased morbidity and mortality from respiratory and cardiovascular diseases. The increase in certain diseases (cardiovascular diseases, hypertension, respiratory diseases, malignancies, infectious diseases, and parasitic infestations) may be due to modern lifestyles as well as air pollution. The APHEA project, "Air Pollution and Health: A European Approach," is one of the epidemiological studies monitoring the short-term effects of air pollution using various health parameters. Particular attention is given to daily variability in lung function, frequency of hospitalization, and mortality. In Paris, the risk of death from respiratory diseases increased by 17% with a 100 μg/m³ rise in particulate matter. Particulate matter, black smoke, and sulfur dioxide (SO_2) are associated with emergency admissions for respiratory diseases. A Spanish study found that oxides, particularly nitrogen dioxide (NO_2) and ozone, are linked to mortality from cardiovascular disease, especially in summer. The carcinogenic effect of many toxic compounds has also been proven.
To date, several hundred different pollutants have been identified (the most important and frequent are listed in Table 1), and the possible formation of new pollutants under the influence of sunlight and electrical discharge should be monitored. Air quality is determined by the concentration of pollutants in the air or by their deposition on surfaces over time. Pollutant concentration is the mass, volume, or quantity of substances contained in a given volume or mass of air.

Table 1. *Pollutant compounds and sources of pollution*

Pollutant compound	The main source of pollution
Sulfur dioxide SO_2	Combustion of coal, oil, heavy metallurgy and related
Hydrogen sulfide H_2S	Chemical processes, refineries
Carbon monoxide CO	Combustion
Nitrogen oxides NO_x	Combustion
$C_n H_{n+2}$	Evaporation of liquid fuels and exhaust gases
Soot	Burning
Particle suspensions	Technological processes, quarries, cement production
Vapors of organic compounds	Chemical processes, oil production, gasoline distribution

In addition to the concentration of pollutant compounds from pollutant sources, air quality in an area is also determined by meteorological elements and conditions: air pressure, wind direction and speed, eddy currents, humidity, fog, rainfall, air temperature, and temperature inversion. The highest concentration of pollutants spreads horizontally in the direction of the wind. During periods of "calm", when there is no air movement, all pollutants remain in the populated area. In the lower layers of the atmosphere, the air is warmer and moves towards the upper, colder layers, which allows normal dispersion. However, rapid cooling leads to a temperature inversion. The air at ground level is colder than the air in higher layers, so dispersion is not possible. Low air pressure, calm conditions, high humidity, haze, and temperature inversion reduce the dispersion of pollutants at height and distance, keeping them at ground level and concentrating them near the source of pollution. Smog can form along with compounds that are extremely toxic and dangerous to human health. The level of pollutants is determined by measurements [1,2].
Air pollution can be transported over long distances from its source. The distance depends on the rate of dispersion (diffusion) of the polluted air masses and the rate of deposition of the polluting compounds. For these reasons, it is necessary to predict the dispersion of air pollution under given conditions. This is achieved through modeling, which we have carried out and present the results in this paper.
To estimate the dispersion of air pollution, it is necessary to know the quality (physical and physicochemical properties) of the pollutants and the quantity (amount/contribution), as the effect of each pollutant depends on these factors.

AIR POLLUTION PROPAGATION MODEL

The distribution of particles in the atmosphere is of great interest to many areas of human activity. Growing awareness of the importance of these processes has enabled continuous measurement for monitoring and data collection. Empirical models of air pollution have been created based on these measurement results. Subsequently, considerable efforts have been made to develop methods for analyzing particle diffusion in the atmosphere. As a result, research findings are used to predict the consequences of emergencies, including various accidents involving the dispersion of hazardous compounds. Despite significant efforts, there are no generally recognized models for analyzing the distribution of air pollution. This is objectively due to the diversity and complexity of these processes. Consequently, there are many different types of models. The main characteristic by which the models are classified is whether they are empirical or theoretical [3].

The classical empirical model is the Pasquill-Gifford's model [4], while the Berlyander's model is an example of a theoretical model of turbulent diffusion [2,3]. In empirical models, the physics of atmospheric processes is either not considered or only very roughly approximated. Today, semi-empirical models provide the best results, though only to a limited extent. In these models, the empirical approach is supplemented by well-developed mathematical and numerical methods that allow the analysis of very complex situations and enable the synthesis of results from different experiments, such as meteorological and diffusion conditions, simultaneously.

However, the models also differ significantly depending on the mathematical apparatus used. Empirical models use explicit forms derived from numerous measurements and can be easily processed on microcomputers. Semi-empirical methods employ procedures for the numerical solution of partial differential equations that describe the observed spatial conditions. Theoretical models use various methods, such as dimensional analysis, analytical solutions of partial differential equations, and simulation methods such as Monte Carlo. It should be noted that, in the search for analytical solutions, mainly stationary processes are analyzed, whereas the numerical approach also allows for the analysis of non-stationary processes.

Current models can be categorized according to the spatial and temporal dimensions of their application: local, regional, and global. Local methods analyze air pollution in areas of up to ten kilometers over periods ranging from a few minutes to several hours. Regional models analyze the spread of air pollution within a radius of several tens to several hundred kilometers, with time intervals from several hours to several days. Global models address the spread of air pollution over areas of several hundred to several thousand kilometers, with the time dimension extending to several weeks [5].

Regarding the mathematical processing and treatment of the processes mentioned the models can be categorized into three types: Gaussian, Eulerian, and Lagrangeian models. The equations in these models are derived using different approximation approaches to solve the equations of turbulent diffusion. The simplest model for calculating the concentration of particles or pollutants on the ground is the statistical Gaussian model. This model assumes that particles emitted from continuous point sources form a plume in which the particle distribution follows a Gauss normal distribution (Fig. 1).

- In this model, wind speed is taken as a parameter from the nearest meteorological station, and it is assumed that this speed is maintained during the time required to transport the dirt particles over a distance of 20 – 30 km. The disadvantages of this model are:
- It assumes that the vertical and horizontal propagation of particles are independent;
- Wind speed components are not considered—a linear path of the particles is assumed;
- The shape of the dispersion, which describes the spread of the particle cloud, depends on the distance from the source;
- Initially, it is assumed that the concentration of particles at the source is infinitely high;
- This model cannot be used to calculate particle concentrations for low wind speeds (less than 1 m/s).

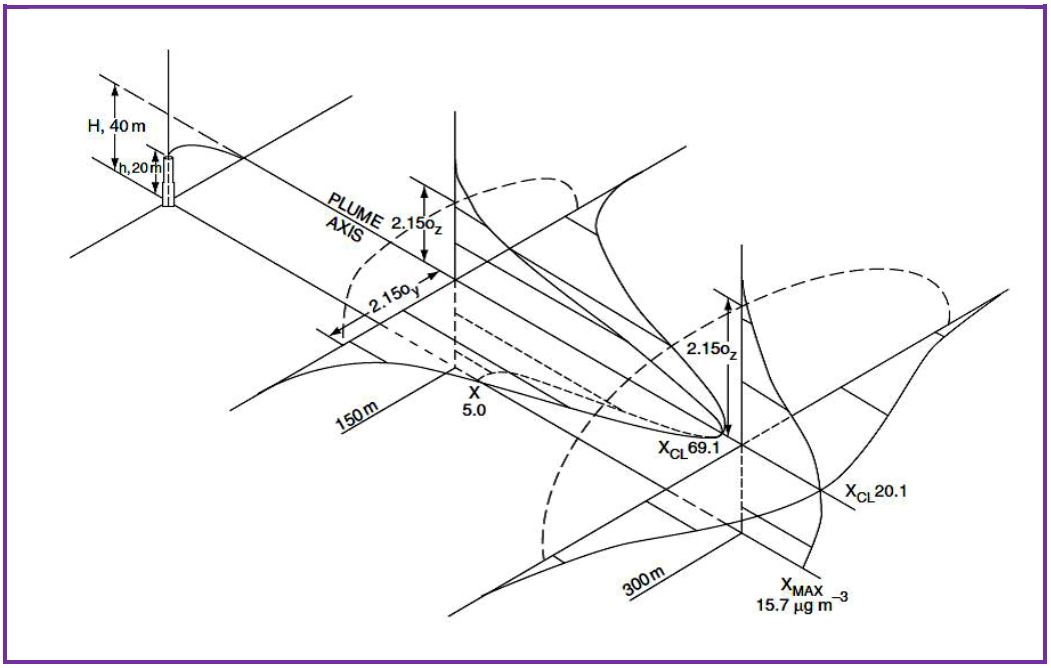


Fig. 1. *Gaussian model of particle emission from a point source [2,6]*

Euler's model is based on the solution of the semi-empirical equation for turbulent diffusion [5]:

$$\frac{\partial q}{\partial t} = -\vec{V} \cdot \nabla q + \frac{\partial}{\partial x}\left(k_x \frac{\partial q}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial q}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial q}{\partial z}\right), \quad (1)$$

where $\vec{V} \cdot \nabla q$ defines the corresponding component of the equation, k_x, $k_y$and$k_z$are the turbulent diffusion coefficients, and q is the mean value of the impurity concentration.

Euler's model of impurity diffusion accounts for the fundamental characteristics of this process: the transport of particles along the direction of convection or flow. It considers turbulent diffusion, convection, spatio-temporal inhomogeneity of scattering parameters, interaction of particles with the Earth's surface, and other factors. This model enables calculation of particle concentration in an area 50 km from a point or other sources that continuously emit pollutants, under any meteorological conditions and over ground surfaces of any relief. It also provides data on pollutant concentrations in low wind speeds, even during stable weather. The model must yield results for the spatial distribution of contaminant concentrations that are consistent with empirical models. The turbulence coefficients depend on wind speed, atmospheric conditions, surface relief, the distance pollutants travel from the observation point, and the position of the pollution source:

$$k_z = U_z \frac{\kappa^2 h_{SBL}}{\ln(z_r/z_0)} \left(\frac{x}{x_1}\right)^b \quad ; \quad k_y = k_z P^{-1}, \quad (2)$$

where U_z represents the wind speed measured at height z_r above the ground, z_0 is the characteristic of the surface relief, κ is the Karman constant, h_{SBL} is the height near the base level of the atmospheric layer, x is the distance travelled by the impurity particle from the source to the observation point, x_1 is the standard distance corresponding to 1000 m, b is the exponent of the power function, and P is the turbulence anisotropy coefficient.

In general, the task of mathematically predicting air pollution is defined as solving the corresponding turbulent diffusion equation with appropriate initial and boundary conditions. Equation (2) describes the spatial distribution of mean concentrations and their change over time, and can therefore be regarded as a prediction equation.

The analytical approach to solving the atmospheric diffusion equations is highly complex and can only be addressed through a series of approximations. Difficulties in obtaining analytical solutions arise even in simple cases. However, if it is assumed that wind speed varies logarithmically with height and the linear and/or energy dependence of the coefficients is removed, finding an analytical solution becomes easier. Studying atmospheric diffusion over a surface with complex relief requires accounting for the variation of many meteorological elements, each of which complicates and often renders an analytical solution practically impossible. Therefore, numerical approaches are the only viable method for integrating the turbulent diffusion equations. Regardless of the capacity and capabilities of computer resources, the parameters of the equation must be chosen carefully to successfully determine the distribution of air pollution [7].

SOLUTION OF A QUASI 1D PROBLEM

This section analyses the dispersion of air pollutants near a point source. The spatial distribution of the pollutant is examined when diffusion, absorption, and air flow processes are present. We focus on a quasi-linear, extended one-dimensional problem, as the aim is to estimate the spatio-temporal distribution of concentration from the air pollution source according to the specified pollution dynamics. Although the choice of a one-dimensional problem is an idealisation, it is justified by the inclusion of virtually all relevant physical mechanisms involved in the displacement of pollutant particles [8]. Furthermore, we have introduced the source function in an analytical form that accurately reflects the operation of an industrial plant. The turbulent diffusion equation for the case under consideration [9] is:

$$\frac{\partial q}{\partial t} + u\frac{\partial q}{\partial x} - b^2\frac{\partial^2 q}{\partial x^2} + cq = A\varphi(t)\delta(x), \tag{3}$$

where u is the wind speed in the direction of the x-axis, b is the impurity diffusion coefficient, $A\varphi(t)$ is a function of the amount of emitted impurity particles per unit time and c is the coefficient characterising the absorption of impurity particles (which can be determined after chemical analysis of the atmospheric processes leading to the transformation and absorption of impurities).

To make the process described by equation (3) more realistic, we assume that $\varphi(t)$ is a periodic function, defined by the following form [7]:

$$\varphi(t) = \begin{cases} 0, & t \in (0, t_1), \quad t_1 < 0\,; \\ 1, & t \in (t_1, t_2), \quad t_2 < 2T\,; \\ 0, & t \in (t_2, 2T), \quad t_2 > t_1\ . \end{cases} \tag{4}$$

Therefore, the point source emits toxic compounds during the interval $t_2 - t_1$. In this case, the boundary and initial conditions are: $q(\pm\infty, t) = 0$ and $q(x, \pm\infty) = 0$. It should also be noted that the postulated equations describe the mean concentration values. The following parameter values are assumed in equation (3): the accepted value for the diffusion coefficient refers to CO_2. Using a numerical approach with the mathematics package *Mathematica*, the required solution was obtained and is shown graphically in the diagrams in Figure 2.

Fig. 2a shows the spatio-temporal distribution for a wind speed of 1 m/s, while Fig. 2b shows the same distribution for a wind speed of 4 m/s. Fig. 2c presents both cases together for easier comparison. The concentration decreases over time, more slowly at higher wind speeds. Additionally, the concentration decreases with distance from the source (in this example, 5 mg/m^3 for a distance of 3 km).

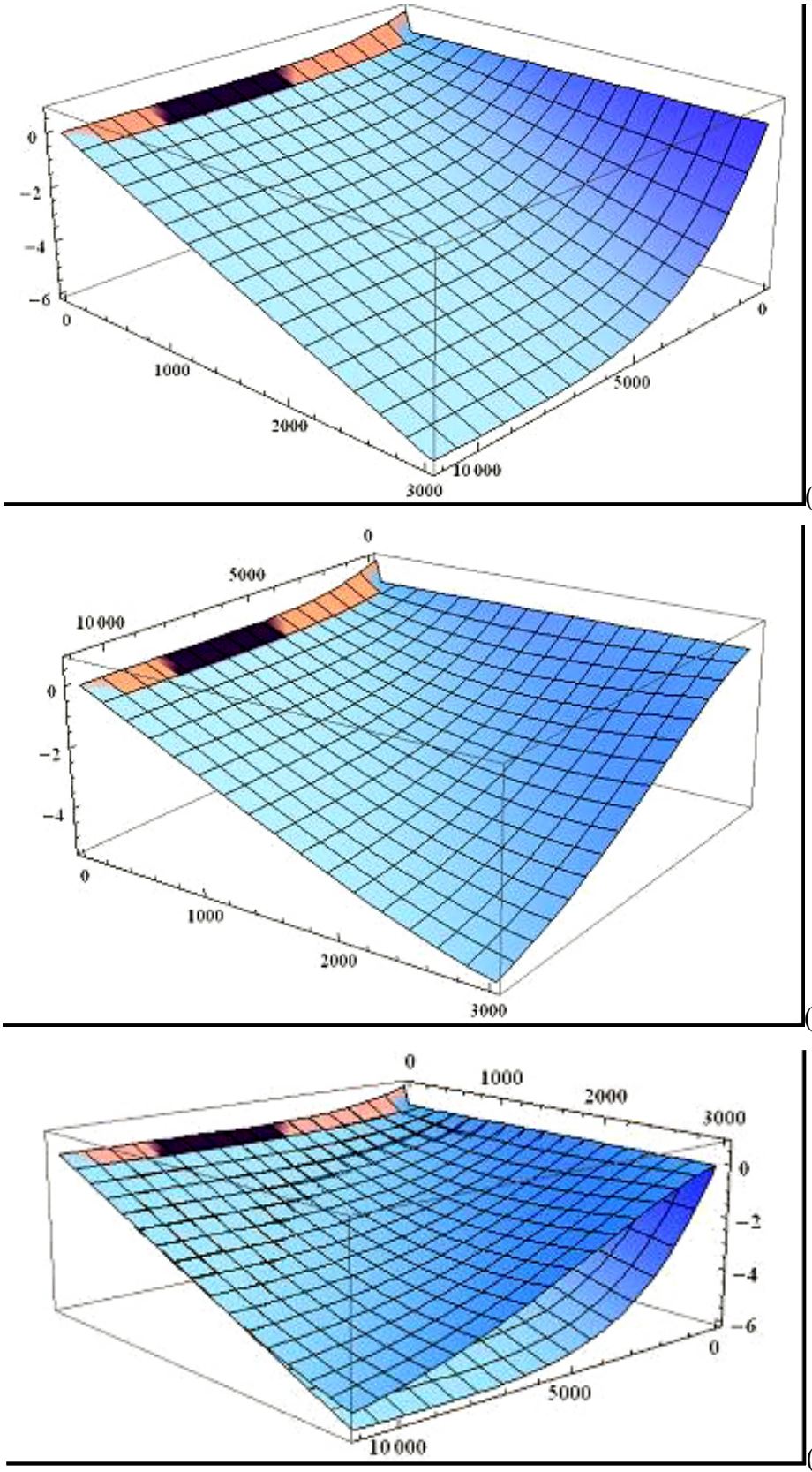


Fig. 2. *Spatial and temporal distribution of impurity concentrations for wind speeds of 1 m/s (a) and 4 m/s (b). Both cases are shown together in (c) for easier comparison*

CONCLUSION

The problem of air pollution is closely linked to the development of industry and transport. Environmental monitoring, particularly of the atmosphere, is carried out in all countries. The effectiveness of this process depends on two components: direct monitoring, which involves measuring air quality using specialized instruments integrated into a unified system that forms the basis of atmospheric monitoring; and indirect monitoring, which involves theoretical modeling of air pollution. This modeling enables the determination of toxic compound concentrations in areas not covered by direct measurements and allows the prediction of pollution distribution in the event of an incident. Thus, modeling is included as part of the overall air pollution monitoring system.

With improved mathematical methods for analyzing the transfer and dispersion of gaseous, liquid, and solid components of air pollution, theoretical modeling is becoming an increasingly effective tool for studying the state of the atmosphere. Determining the level of air pollution by applying an appropriate distribution model allows simulation of the dispersion of toxic compounds for different assumed emission intensities under topological, urban, and meteorological conditions.

With a theoretical approach and the development of a suitable mathematical-physical model, a realistic representation of the dispersion of pollutant particles into the surrounding atmosphere can be achieved, providing a basis for assessing hazard potential. Using a simplified one-dimensional model of a periodic (industrial) point pollutant, we have visualized the spatio-temporal distribution of pollutant concentration downwind (for two different velocities) from the source to a point 3 km away. We have shown that the pollutant concentration decreases over time from the moment the emission stops, and that this decrease is slower at higher wind speeds. Additionally, the pollutant concentration decreases almost linearly with distance from the source.

REFERENCES

[1] Tiwary A., Colls J., Air Pollution, New York, Routledge, 54-90, 2010.
[2] Jaćimovski S.K., Miladinović S., Ilijazi V., Zorić V.M., Šetrajčić I.J., Armaković S., Šetrajčić J.P., Linear Expansion of Air Pollution, Proceedings 2nd UrbanEco, Zrenjanin, 62-67, 2012.
[3] Berlyander M.E., Contemporary Problems of Atmospheric Diffusion of Atmospheric Pollution, Leningrad, Gidrometeoizdat, 11-18, 1975.(In Russian)
[4] Pasquill F., Smith F.B., Atmosperic Diffusion, New York, J.Wiley&Sons, pp. 20-80, 1983.
[5] Stepanenko S.N., Voloshin V.G., Tipcov S.V., Turbulent Diffusion Equation Solution for the Stationary Point Source, UGZ **3**, 13-25, 2008.
[6] Lazaridis M., First principles of Meteorology and Air Pollutant, New York, Springer, 201-232, 2011.
[7] Berlyander M.E., Forecast and Control of Atmospheric Pollution, Leningrad, Gidrometeoizdat, 8-79, 1985.(In Russian)
[8] Tošić B.S., Stojanović S.D., Škrinjar M.J., Kapor D.V., The One Dimensional Problem of Air-Pollutant Distribution, Faculty of Sciences – Universityof Novi Sad, Review of Research 12, 79-88, 1982.
[9] Marchuk G.I., Mathematical Modeling in the Environmental Problem, Moskwa, Nauka, 175-187, 1982. (In Russian)

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SOFTWARE QUALITY MONITORING IN AGILE WORKING ENVIRONMENT

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Abstract: The Goal of this paper is to review software quality in agile environments as well as software quality monitoring in agile working environments. An overview of ISO standards for different quality aspects has also been reviewed, as it proposes the international standardization scope for quality evaluation. Besides functional and non-functional aspects of software quality during the software development lifecycle, psychological factors were also considered.
Key words: software quality monitoring, agile working environment, ISO, quality standardization, functional aspects, non-functional aspects, software development lifecycle

INTRODUCTION

This research focuses on the quality aspects of software development, along with the agile development approach used throughout the development process. By analyzing three different ISO standards related to quality (ISO/IEC 25010:2023, ISO/IEC/IEEE 12207:2017, and ISO/IEC 25019:2023), this review outlines a strategy for building high-quality software products within an Agile team environment. Mentioned ISO standards cover both the functional and non-functional quality characteristics that are required for delivering reliable and high-quality software. Agile practices were covered, showing how quality can be maintained even in fast-paced, iterative development cycles. It also observes how Agile teams can use these standards to guide their work, making sure that the software meets user requirements while also performing well and adapting to change. Overall, this research provides an overview of how Agile teams can balance technical quality with flexible, collaborative ways of working to achieve better, quality-focused software outcomes.

Agile Software Development

Agile Software Development is a methodology where a software product is developed through iterations, while delivery is done incrementally. Considering the delivery itself, it is frequent, with the ability to adapt to customers' requirements changes [1]. Since software development utilizes a creative approach by using self-organized, cross-functional teams, overall collaboration is very important. Project managers and developers claim that agile software development means SCRUM or XP. Thus, by refining the question of what agile software development is (by adding more factors to the question), the answer becomes blurry. Sometimes, the definition of agile software development contradicts itself, regarding the terminology and existing concepts. However, pure agile or traditional software development happens very rarely, and most practices are only close to being agile [2]. Since agile methodology became widespread in organizations that mostly relied on traditional or structured development methods, such as the waterfall approach, in order to increase the benefits of different methods, organizations started a hybrid approach that combines agile, waterfall, and structured software development methodologies [3]. Therefore, due to the nature of agile methodology itself, there are obstacles for adopting quality assurance mechanisms to some level [1].

International Organization for Standardization

ISO/IEC 25010:2023 Systems and Software Engineering - Systems and Software Quality Requirements and Evaluation (SQuaRE) - Product Quality Model considers the information and communication technology products, as well as software products for organizational and personal activities, and is composed of nine characteristics (divided into subsets) that relate to quality properties of the products. These characteristics are used to describe and evaluate the quality of a software product from multiple perspectives. Main characteristics are functional suitability (how well the product provides the required functions), performance efficiency (how the product performs in relation to the resources it uses), compatibility (how the product can work with other systems), and interaction capability (the product's ability to support communication and cooperation with users and other systems). Other characteristics include reliability (the stability of the product during normal use), security (the protection of data and control of access), maintainability (how easily the product can be changed or updated), flexibility (the ability of the product to adapt to changes in the environment or requirements), and safety (the protection of people, property or the environment during system operation) [4].
ISO/IEC/IEEE 12207:2017 Systems and software engineering - Software Life Cycle Processes considers the processes, activities and tasks which take place during the acquisition (when software is obtained from an external source), supply (when software is provided to a customer), development (when software is created or modified), operation (when software is used in its intended environment), maintenance (when software is updated, corrected or improved), or disposal (when software is retired or removed from use) of software systems, products and services, while the full life cycle of software systems, products or services is considered. The standard defines a process model that includes technical and management aspects of software engineering and supports the organization and control of software work across all phases. It includes process definitions that guide the planning (defining the work to be done), implementation (carrying out development activities) and control (monitoring and managing progress) of software development and maintenance, as well as supporting processes (activities that assist development, such as documentation or testing) and organizational processes (activities related to managing resources, infrastructure and quality) that help manage quality, configuration, documentation and other important aspects across the software life cycle [5].
ISO/IEC 25019:2023 Systems and Software Engineering - Quality Requirements and Evaluation (SQuaRE) - Quality in Use Model provides a set of quality characteristics for specifying, measuring, evaluating and improving quality in use (the degree to which a software product meets user needs during actual operation), where the focus is on the user's experience with the product during real tasks in a real context. This standard expands the concept of software quality by introducing characteristics that describe how well users can achieve their goals (effectiveness), how efficient the software is during actual use (efficiency), how satisfied users are (satisfaction), how well the system avoids risks (freedom from risk), and how effectively it works in different usage contexts (context coverage). The model is intended to support the development of systems that meet both user expectations and quality goals from the perspective of people who interact with the software directly[6].

RELATED WORK

Software Quality in an Agile Environment

Management of quality requirements in the agile software development context is considered a challenging task [7]. Agile development methodology mechanisms of quality assurance must be established to ensure high-quality software production. Addressing quality issues is one of the important factors, and adopting the correct strategy is of great importance in the early stages of development. To ensure quality, two distinct techniques can be employed, which are constructive and analytic techniques. While constructive techniques consider prototyping, specification techniques (such as standards and processes), and elicitation techniques,

analytic techniques, on the other hand, focus on dynamics (validation and testing) and statics (verification and inspection) [1]. Since agile methodology considers working software products as a priority, development is divided into iterations (sprints), where each iteration (sprint) consists of planning, designing, development, testing, and feedback. The foundation of each iteration is a backlog, which is interpreted as a user requirement. However, user requirements can change, and the possibility of re-prioritizing features of development can be introduced. Regarding the possible changes, after iteration delivery, the customer performs a review and provides comments to determine the status of a product (iteration can be accepted, rejected, or requested for a change). Since iteration review presents a significant quality assurance mechanism in the agile development process, there are three important factors for each iteration to ensure higher quality, and they are the customer's availability (feedback on the current stage of development), communication medium (distance barrier, emails, telephone), and supporting tools (documentation) [1].
Regarding different aspects that have an impact on the quality of software, quality requirements themselves should be observed as well. They are considered non-functional requirements since they describe non-functional aspects of software such as maintainability, reliability, performance, and security. However, regardless of a software product being delivered, a system may not be regarded as good by the user if it does not meet certain performance, usability, or similar [8].
One more factor that impacts the overall software quality in an agile environment, according to [9], is agile software testing. By carefully planning and implementing agile testing practices such as continuous integration, test-driven development, and pair programming, software quality is improved by reducing defects and improving maintainability.
Dwelling deeper on the non-functional aspects of software quality, characteristics of functionality, reliability, usability, efficiency, and maintainability should be observed. Functionality represents a set of software attributes that have specific properties that provide functions that are required by the user. Reliability considers the ability to maintain specific levels of performance under specific conditions for a certain amount of time. Usability is a term used for software attributes that represent a measure of the effort needed for users to learn to use the product. Efficiency is a set of software attributes for the ability of the software product to provide a relationship between the level of performance of the said software, and the amount of resources that are used under stated conditions. Finally, maintainability represents a set of software attributes that are required to avoid various unexpected effects from specified modifications [10].

Software Quality Monitoring in an Agile Environment

The process of software engineering is useful for organizing development activities within the software development life cycle (SDLC). Common SDLC begins by analyzing the project's requirements and goes through the system's design, implementation, testing, deployment, and maintenance. The main goal of the agile methodology focuses on the ability to change, by minimizing cost and unnecessary rework, which is mostly found in traditional software engineering practices [11].
Agile methods are expected to deal with many unstable requirements by utilizing various techniques. Most notable techniques were simple planning, short iteration, early release, and frequent customer feedback. By performing those techniques, agile methods are able to deliver product releases in a much shorter period of time, when compared to the waterfall approach. However, there are several quality techniques that can be imposed to increase overall quality assurance, and they are: on-site customer, refactoring, acceptance testing, and early customer feedback. Observing the first quality technique, On-Site customer practice is something commonly found in agile methodology. By supporting the development team through the whole development process, customers can refine and correct requirements. Second quality technique - refactoring is considered a technique of restructuring an existing body of code by altering its internal structure without changing its external behavior. Each refactoring action should be small and should be done in sequence to prevent possible errors. This makes an

existing system resilient to getting seriously broken during the reconstruction. Third quality technique - acceptance testing, is a type of testing that is performed after all unit test cases have passed. Contrary to waterfall acceptance testing, agile acceptance testing occurs much earlier and more frequently and is done many times during iterations. Finally, the quality technique of early customer feedback is considered the most valuable characteristic of agile methods. By having short releases and quick movement to a development phase, the team is able to get customer feedback as soon as possible, which may provide valuable information for the development team [12].

Metrics for Software Quality Monitoring in an Agile Environment

Quality metrics are an important part of software engineering, as they transform both the customer expectation and operational performance into certain metrics that can be measured, evaluated, and compared. Metrics may be influenced by different factors such as functionality, usability, reliability, and portability [13]. Regarding the metrics of quality assessment, the Q-Rapids Tool is a result of a project whose main goal is to provide continuous quality assessment to support decision-makers in the management of quality in agile software development. Different metrics can be performed in correlation with the Q-Rapids quality model. The quality model itself consists of Quality Metrics, which are low-level indicators measuring a specific characteristic that is assessed from raw data stored in a data source. Later, Quality Metrics are aggregated into Quality Factors, which define significant concepts in relation to quality. After that, Quality Factors are combined to compute higher-level model elements, which are Strategic Indicators. Considering the quality assessment, the Q-Rapids Tool is used to gather data from heterogene, external data sources. After that, data is aggregated into Strategic Indicators following the Q-Rapids Quality Model. Predictions of the quality assessment are used to assist decision-makers in their decisions, considering product evolution. By using prediction techniques such as ARIMA, ETS, and Neural Networks, the evolution of strategic indicators is assembled. This functionality provides the ability to react to potential issues related to concrete aspects of the product, as well as quality issues that could emerge. However, if a prediction points out possible quality issues, what-if analysis can be used to evaluate improvement options and their impact on strategic indicators. Regarding that, quality assessment could be below some user-defined thresholds for one or more quality model elements, and due to Quality Requirement Semi-automatic Generation, a quality alert may be generated [7].

Psychological Factors

Psychological safety in an agile environment can enhance software quality by utilizing constructive and supportive environments. That kind of environment emphasizes learning from mistakes and encourages quality-related error reports, where mistakes can be turned into opportunities and continuous learning. Knowledge sharing and skill expertise are aimed at enhancing software quality, especially when team members feel more comfortable and contribute to the collective knowledge pool. Regarding the safety and psychological factor, human needs should be met, but it requires companies, management, agile teams, and their individual members to uphold and propagate norms that foster a sense of safety [14].
Regarding the self-organizing teams, handling the complexity and pressure of deadlines during the project development phase can be improved in a self-organized environment. Decisions may be taken on behalf of a self-organized team, and they could adapt accordingly to the situation. Contrary to command-and-control teams, self-organizing teams may have improved chances for personal development instead of solely focusing on completion of the project. By having a mature enough organization, productivity may increase, and dynamic changes may be more welcome even in the late implementation phase. Team size could impact the overall time required for certain actions as well, where fewer but more competent, experienced developers could deliver desired outputs in less time, with better quality [15].

RESULTS AND DISCUSSION

In this paper, the primary contribution was to review existing literature related to software quality and software quality monitoring in an agile environment, with a focus on functional and non-functional quality aspects and their impact on software quality while taking ISO standards into account.

CONCLUSION

In conclusion, Agile software development plays an important role in improving overall software quality by addressing both functional and non-functional aspects through the development process. Functional quality focuses on whether the software meets intended requirements, such as delivering the right features and behavior of software, while non-functional quality considers how well software performs under certain conditions, such as speed, reliability, security, and ease of use. The iterative approach of agile software development allows teams to continuously improve both types of quality through continuous testing and feedback. Self-organization of teams may benefit from psychological factors like autonomy, shared responsibility, and motivation while encouraging better collaboration, faster and more accurate decision-making, as well as more creative problem-solving. Together, both technical and human factors enable agile teams to adapt to change effectively and deliver high-quality software that meets both user needs and system demands.

REFERENCES

[1] R. Shuib and S. Hassan, "Towards adopting software quality assurance in agile development methodology," Turkish Journal of Computer and Mathematics Education, vol. 12, no. 3, pp. 2152–2157, 2021.
[2] M. Kuhrmann et al., "What makes agile software development agile?," IEEE transactions on software engineering, vol. 48, no. 9, pp. 3523–3539, 2021.
[3] A. Mishra and Y. I. Alzoubi, "Structured software development versus agile software development: a comparative analysis," Int J Syst Assur Eng Manag, vol. 14, no. 4, pp. 1504–1522, Aug. 2023, doi: 10.1007/s13198-023-01958-5.
[4] "ISO/IEC 25010:2023(en), Systems and software engineering — Systems and software Quality Requirements and Evaluation (SQuaRE) — Product quality model." Accessed: Sept. 04, 2025. [Online]. Available: https://www.iso.org/obp/ui/en/#iso:std:iso-iec:25010:ed-2:v1:en
[5] "ISO/IEC/IEEE 12207:2017(en), Systems and software engineering — Software life cycle processes." Accessed: Sept. 03, 2025. [Online]. Available: https://www.iso.org/obp/ui/en/#iso:std:iso-iec-ieee:12207:ed-1:v1:en
[6] "ISO/IEC 25019:2023 - Systems and software engineering — Systems and software Quality Requirements and Evaluation (SQuaRE) — Quality-in-use model." Accessed: Sept. 04, 2025. [Online]. Available: https://www.iso.org/standard/78177.html
[7] L. López, A. Bagnato, A. Ahberve, and X. Franch, "QFL: data-driven feedback loop to manage quality in agile development," in 2021 IEEE/ACM 43rd International Conference on Software Engineering: Software Engineering in Society (ICSE-SEIS), IEEE, 2021, pp. 58–66. Accessed: Sept. 03, 2025. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/9402163/
[8] P. Karhapää et al., "Strategies to manage quality requirements in agile software development: a multiple case study," Empir Software Eng, vol. 26, no. 2, p. 28, Mar. 2021, doi: 10.1007/s10664-020-09903-x
[9] M. I. Khan et al., "Analysis of Agile Software Testing, It's Impact on Software Quality and Cost," Int. J. Comput. Intell. Control Copyrights@ Muk Publ, vol. 14, no. 1, pp. 974–8571, 2022

[10] B. Dugalic and A. Mishev, "ISO Software Quality Standards and Certification.," in BCI (Local), 2012, pp. 113–116. Accessed: Sept. 03, 2025. [Online]. Available: https://ceur-ws.org/Vol-920/p113-dugalic.pdf
[11] A. Thool and C. Brown, "Securing Agile: Assessing the Impact of Security Activities on Agile Development," in Proceedings of the 28th International Conference on Evaluation and Assessment in Software Engineering, Salerno Italy: ACM, June 2024, pp. 668–678. doi: 10.1145/3661167.3661280.
[12] M. Huo, J. Verner, L. Zhu, and M. A. Babar, "Software quality and agile methods," in Proceedings of the 28th Annual International Computer Software and Applications Conference, 2004. COMPSAC 2004., IEEE, 2004, pp. 520–525. Accessed: Sept. 06, 2025. [Online]. Available: https://ieeexplore.ieee.org/document/1342889/
[13] K. Chakravarty and J. Singh, "A Study of Quality Metrics in Agile Software Development," in Machine Learning and Information Processing, vol. 1311, D. Swain, P. K. Pattnaik, and T. Athawale, Eds., in Advances in Intelligent Systems and Computing, vol. 1311. , Singapore: Springer Singapore, 2021, pp. 255–266. doi: 10.1007/978-981-33-4859-2_26.
[14] A. Alami, M. Zahedi, and O. Krancher, "The role of psychological safety in promoting software quality in agile teams," Empir Software Eng, vol. 29, no. 5, p. 119, Sept. 2024, doi: 10.1007/s10664-024-10512-1.
[15] A. Ahmed, S. Ahmad, N. Ehsan, E. Mirza, and S. Z. Sarwar, "Agile software development: Impact on productivity and quality," in 2010 IEEE International Conference on Management of Innovation & Technology, IEEE, 2010, pp. 287–291. Accessed: Sept. 06, 2025. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/5492703/

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HYGIENIC CORRECTNESS OF DRINKING WATER OF ZRENJANIN

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Abstract: Drinking water must be safe for the health of the people who consume it. The quality of drinking water consists of physico-chemical and microbiological parameters. In order to preserve the microbiological integrity of drinking water, it is necessary to continuously monitor the source and the distribution network, as well as maintain them. Disinfection of raw water by chlorination is also necessary. The aim of this work is to examine the physico-chemical and microbiological parameters of drinking water and indicate risk analysis, control measures that can affect the prevention and elimination of pollution in order to maintain the microbiological integrity of drinking water in the city of Zrenjanin.
Key words: drinking water, physico-chemical parameters, microbiological control

INTRODUCTION

Drinking water that is used for public supply to the population or for the production of foodstuffs intended for sale is subject to testing for hygienic correctness carried out by authorized health institutions [1,2].
The origin of the drinking water of the Middle Banat district is from the second and third aquifers, from depths of about 60-130m. Water is disinfected with chlorine preparations and distributed to consumers without any purification process [3,4,5]. The dominant way of water supply is central. For each drinking water quality parameter, there are standards for maximum allowable concentrations. The results of all physical, chemical and microbiological parameters of drinking water should be within the permitted limits and to meet the applicable regulations for quality and health safety drinking water.
The town of Zrenjanin is supplied with water from a source located on the road to Mihajlovo. In the current mode of operation of the "Mihajlovačka" spring, 220 l/s is exploited on average (on an annual basis). Of the measures to correct the quality of underground water, only disinfection is carried out.
At the "Mihajlovačka" source, 57 wells were built, in two lines at a distance of about 1250 meters, of which 32 are in active operation. The wells capture water from outcrops that capture aquifers from a depth of 35 to 80 m and from 90 to 140 m. Disinfection of water is carried out in the JKP "Vodovod i Kanalizacija" Zrenjanin by chlorination as preparation of water for drinking and distribution in the city of Zrenjanin.
The preparation process takes place continuously. Two lines of springs are in use, with 15 wells each in use. Pipelines start from each location of the well and extend to the very location where chlorination is performed. The main pipelines are in the direction Mihajlovo-Zrenjanin and supply the city with water [6].
The purpose of adding a secondary disinfectant is to maintain the quality of drinking water in the distribution system to the final consumer, that is, to maintain the achieved level of water quality.
The most important pipelines in the existing distribution network of the city of Zrenjanin that transport the necessary amounts of water to the main connections of the distribution network and carry out the final supply and distribution of water to consumers are:
• Western transit pipeline,
• The main supply pipeline to the center and southeastern parts of the city,
• Eastern transit pipeline.
In this paper were analyzed physico-chemical and microbiological parameters samples of drinking water town Zrenjanin. From the analysis of drinking water town Zrenjanin, it is

determined, at any time, if there is deviation from the maximum allowable concentrations of the individual investigated parameters.

MATERIAL AND METHODS

Physico-chemical and microbiological analysis of drinking water samples from the central water supply in the territory of the city of Zrenjanin were conducted in the period from January to June 2021.
Control of the hygienic suitability of drinking water in the city of Zrenjanin was carried out in the accredited laboratory of the "Public Health Institute" in Zrenjanin, in accordance with the criteria prescribed by the Rulebook on the hygienic suitability of drinking water ("Official Gazette of the SRJ", No. 42/98 and 44/99 and "Official Gazette of the RS", No. 28/2019) [7] and the Rulebook on the method of sampling and methods for laboratory analysis of drinking water (Official Gazette of the SFRJ No. 33/87) [8] and Council Directive 98/83/EC and [9].
Physical and chemical analysis of raw and chlorinated water samples were performed:
• Volumetric methods (quantitative determination of organic matter, consumption of $KMnO_4$, chloride content Cl,)
• Electrochemical method (pH value)
• Conductometric method (electrical conductivity)
• Spectrophotometric methods (content: nitrate, nitrite, ammonia, iron, manganese)
For microbiological analysis, samples were taken at 14 points in the city of Zrenjanin, and the following microbiological parameters of the basic "A" scope examination were performed:
• Total number of culturable microorganisms, test method SRPS EN ISO 6222:2010

RESULTS AND DISCUSSION

As for the quality of the underground water used for the water supply of the population and economy of the city of Zrenjanin, although it is not uniform, it can be safely said that the water is alkaline (pH 7.4-8.9), with a total alkalinity of about 650 $CaCO_3$. The color of the water is mostly yellow and is determined by the high content of organic matter of natural origin ($KMnO_4$ consumption is 14-95 mg/l), i.e. the presence of humic and fulvic acids. Increased amounts of organic matter occur due to the impossibility of their decomposition to the ultimate inorganic elements (carbon dioxide, nitrogen, nitrates) due to the lack of oxygen and bacteria in the water, so the organic matter practically remains conserved in it.
According to its inorganic content, the underground water of the source of the water supply in Zrenjanin belongs to the sodium-hydrocarbonate type. Of the cations, sodium dominates, in concentrations of 200-300 mg/l, which are above the maximum permissible concentrations in drinking water, while the concentrations of calcium (2-70 mg/l) and magnesium (7-30 mg/l) are extremely low, which is very rare in deep underground waters.
Of the anions, hydrocarbons dominate (708-970 mg/l), while the concentrations of sulfates (3-90 mg/l), chlorides (5-50 mg/l) and fluorides (0.1-1.0 mg/l) are extremely low compared to the usual values for groundwater.
The content of ammonia (0.1 - 3.2 mg/l) and iron (0.1 - 1.3 mg/l) is generally above the maximum allowed concentration for drinking water. The origin of ammonia is most likely nitrate (created by the reduction of nitrates in anaerobic conditions, as indicated by the low concentrations of nitrates in the tested water samples. Both ammonia and iron have a bad effect on organoleptic properties (ammonia has an unpleasant smell, and iron makes water bitter), but they are not dangerous for the health of consumers.
The quality and safety of the drinking water town Zrenjanin, is observed by physical-chemical and microbiological analysis.Tables 1 and 2 show the results of raw and chlorinated water monitoring, followed by comparative continuous sampling in the first half of 2021.

Table 1. *Raw water analysis results*

The parameters	Unit	Maximum allowed	Sample1 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7
Temperature	°C	source temperature or lower	14,8	15,2	15,4	14,4	16,0	15,6	13,8
Chlorine residual	mg/l	0,5	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Color	°Pt/Co	5	55	51	47	52	40	39	44
Turbidity	NTU	1	0,33	0,11	0,36	0,02	0,02	0,04	0,26
pH	/	6,8-8,5	7,98	8,23	8,19	8,25	8,33	8,26	8,09
Consumption of $KMnO_4$	mg/l	12	43,64	41,13	40,5	45,53	42,39	41,72	42,35
Ammonia (NH_3)	mg/l	0,5	1,93	1,73	1,46	1,42	0,95	1,01	1,48
Chlorides (Cl)	mg/l	250	12,46	12,46	14,48	12,46	5,38	<5	12,12
Nitrite (NO_2)	mg/l	0,03	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Nitrate (NO_3)	mg/l	50,0	<2.2	<2.2	<2.2	<2.2	<2.2	<2.2	<2.2
The rest of the fumes	mg/l	/	819	745	803	807	730	731	775
Conductivity	µS/cm	2500	1322	1234	1258	1253	1125	1155	1169
Iron (Fe)	mg/l	0,3	0,61	0,6	0,58	0,44	0,2	0,22	0,57
Orthophosphates (P)	mg/l	0,15	0,68	0,62	0,7	0,59	0,55	0,45	0,54
Arsenic (As)	mg/l	0,010	0,091	-	-	-	-	-	-
Aerobic mesophilic bacteria			0	6 AMB	4 AMB	0	2 AMB	2 AMB	0

Table 2. *Chlorinated water analysis results*

The parameters	Unit	Maximum allowed	Sample 1	Sample .2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7
Temperature	°C	source temperature or lower	9,1	9,1	9,1	10,0	13,3	14,0	10,6
Chlorine residual	mg/l	0,5	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Color	°Pt/Co	5	46	43	43	42	40	39	40
Turbidity	NTU	1	0,28	0,12	0,31	0	0,02	0,07	0,02
pH	/	6,8-8,5	8,16	8,27	8,240	8,19	8,16	8,27	8,07
Consumption of $KMnO_4$	mg/l	12	39 25	39,82	41,13	40,46	38,62	37,93	39,82
Ammonia (NH_3)	mg/l	0,5	1,06	0,78	0,94	0,83	0,78	0,85	0,98
Chlorides (Cl)	mg/l	250	12,79	10,77	11,11	11,78	10,77	10,77	12,12
Nitrite (NO_2)	mg/l	0,03	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Nitrate (NO_3)	mg/l	50,0	<2.2	<2.2	<2.2	<2.2	<2.2	<2.2	<2.2
The rest of the fumes	mg/l	/	751	749	728,000	758	759	746	769
Conductivity	µS/cm	2500	1233	1168	1193	1192	1157	1185	1182
Iron (Fe)	mg/l	0,3	0,35	0,24	0,31	0,25	0,22	0,24	0,4
Orthophosphates (P)	mg/l	0,15	0,61	0,51	0,6	0,56	0,57	0,51	0,57
Arsenic (As)	mg/l	0,010	0,126	-	-	-	-	-	-
Aerobic mesophilic bacteria			0	0	1 AMB	0	1 AMB	0	0

The diagrams show variations of parameters that exceed the maximum allowed concentrations, namely: color, consumption of $KMnO_4$, ammonia, iron, orthophosphates and arsenic in the analyzed samples of raw and chlorinated water (Fig. 1,2,3,4,5,6).
Based on the diagram, it can be concluded that there are correlations of the decrease in the content of the mentioned parameters, except in the case of arsenic, as a result of oxidation due to chlorination of raw water. The increase in arsenic can be explained by the partially destroyed organic matter from which part of the arsenic was separated, due to oxidation by chlorination.

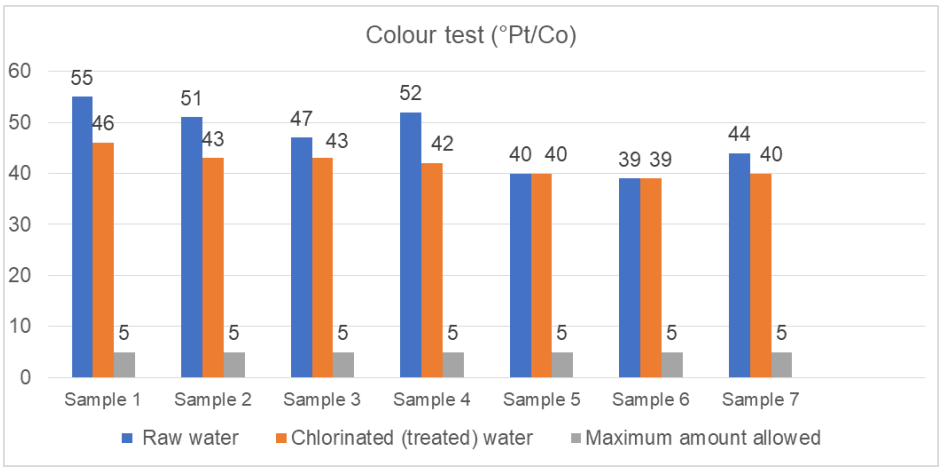


Fig. 1. *Color in the analyzed samples of raw and chlorinated water in relation to the maximum allowed value*

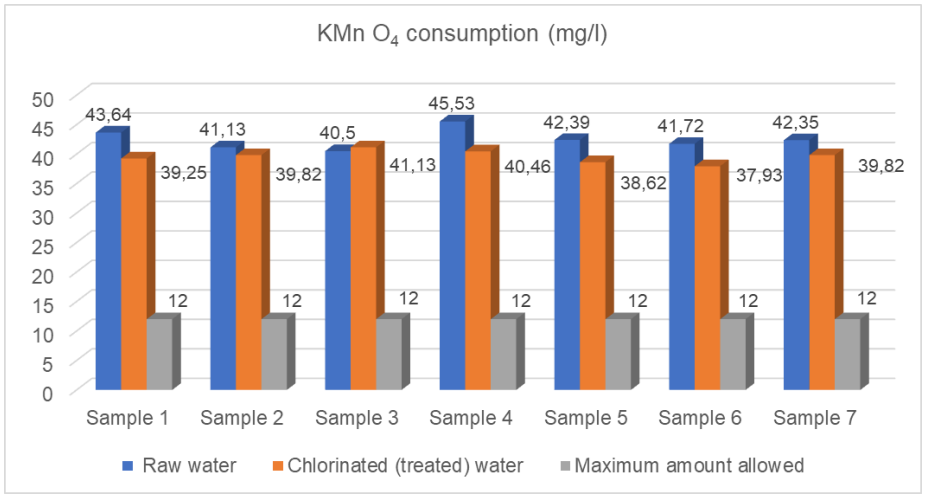


Fig. 2. *Consumption of $KMnO_4$ in the analyzed samples of raw and chlorinated water in relation to the maximum allowed concentration*

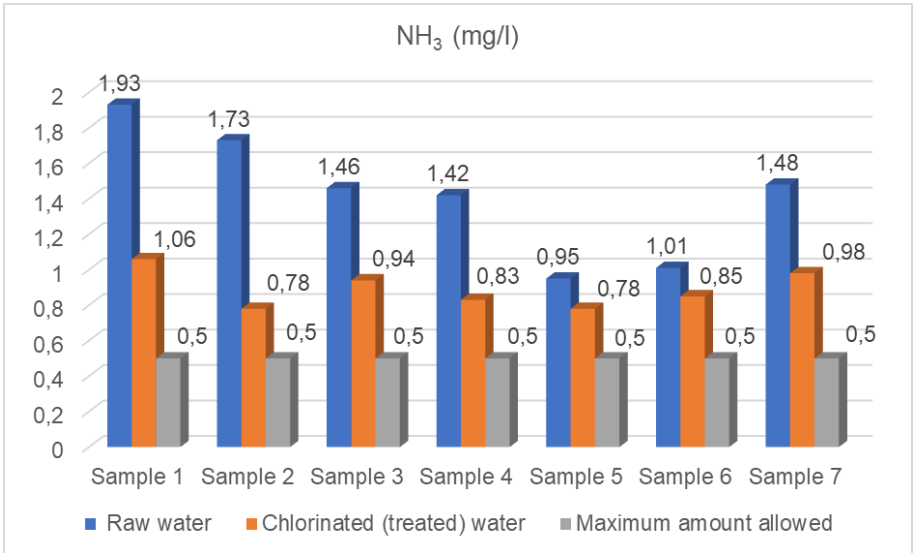


Fig. 3. *Concentration NH_3 in the analyzed samples of raw and chlorinated water in relation to the maximum allowed concentration*

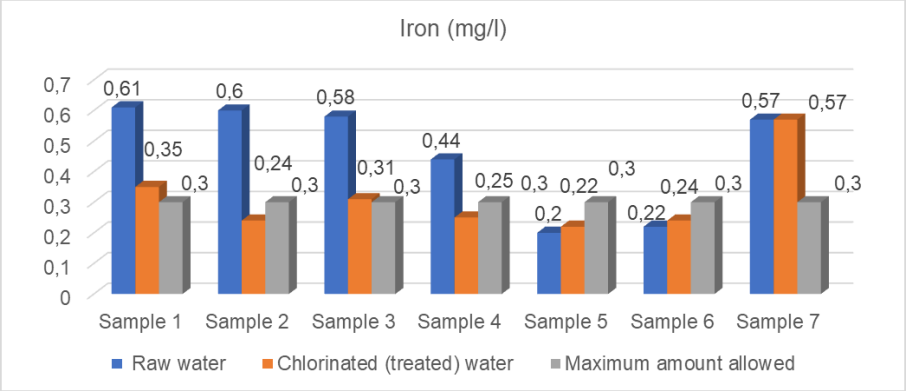


Fig. 4. *Concentration iron in the analyzed samples of raw and chlorinated water in relation to the maximum allowed concentration*

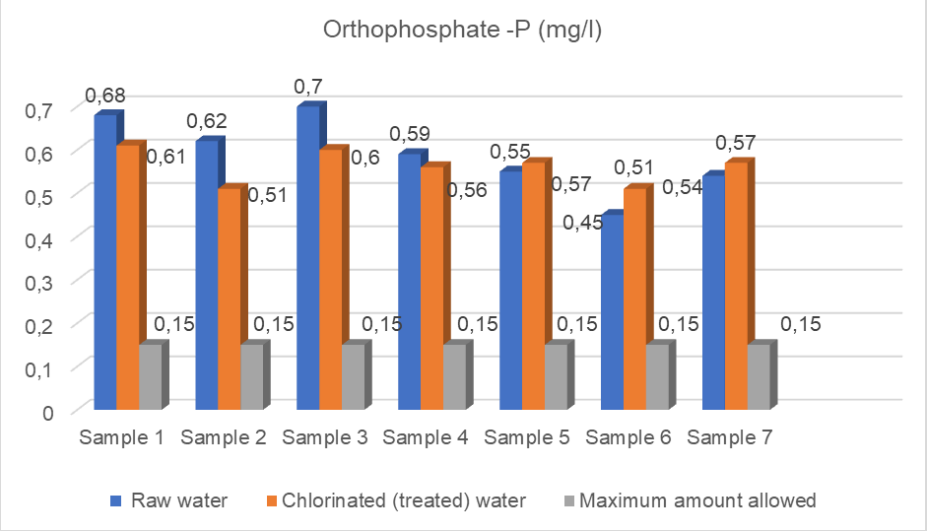


Fig. 5. *Concentration orthophosphate in the analyzed samples of raw and chlorinated water in relation to the maximum allowed concentration*

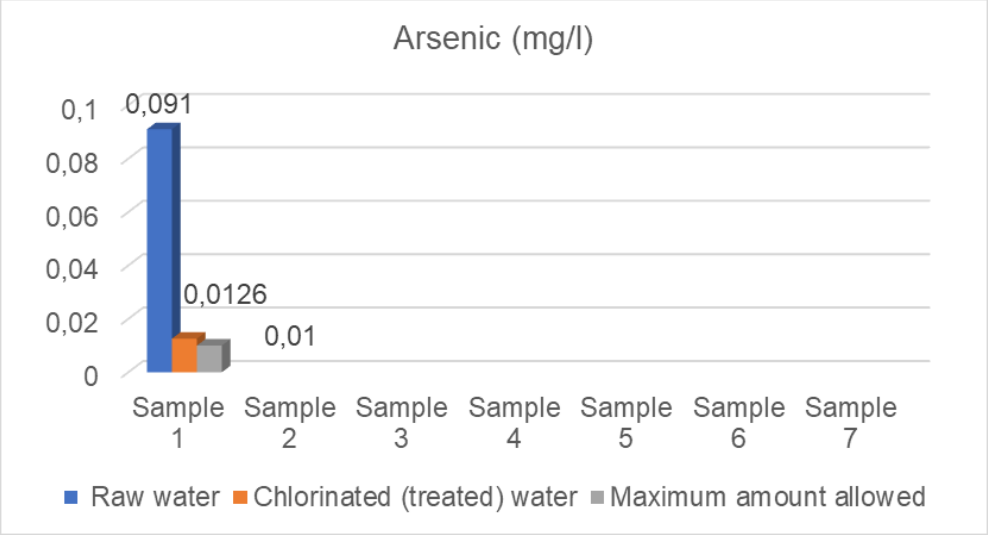


Fig. 6. *Concentration arsenic in the analyzed samples of raw and chlorinated water in relation to the maximum allowed concentration*

CONCLUSION

In the results of the hygienic correctness of the analyzed samples of raw water, one can see variations of parameters that exceed the maximum allowed concentrations, namely: color, consumption of KMnO4, ammonia, iron, orthophosphates and arsenic. The underground water used for the water supply of the city of Zrenjanin has a specific and extremely complex physical and chemical composition of the water, which has been intensively used for decades and will continue to be used as the main drinking water resource in the future.
Thanks to the long-term interaction with the sediments in which it is located, the underground water gradually washed out various mineral and organic ingredients from them, incorporated them into its structure and became increasingly burdened with the taken-over substances. The consequence of that is that the quality of the deep waters of the northern and central Banat, could never satisfy many of the criteria of the rulebook on the hygienic correctness of drinking water.

REFERENCES

[1] Dalmacija, B., Tomin, M.B., Kontrola kvaliteta vode za piće od izvorišta do potrošača, Departman za hemiju, biohemiju i zaštitu životne sredine, PMF, Novi Sad, 2015.
[2] Šćiban, M., Prodanović, J., Tehnologija vode I deo - kvalitet vode i sistem za vodosnabdevanje, Tehnološki fakultet, Novi Sad, 2021.
[3] Dalmacija, B., Agbaba, J Klašnja, M., Savremene metode u pripremi vode za piće, Departman za hemiju, biohemiju i zaštitu životne sredine, PMF, Novi Sad, 2009.
[4] Rowland, A.L.H., Omoregie, O. E., Millot, R., Jimenez, C., Mertens, J., Baciu, C., Hug J. S., Berg, M., Geochemistry and arsenic behaviour in groundwater resources of the Pannonian Basin (Hungary and Romania), 26, pp, 1-17, 2011.
[5] Barringer, L. J., Mumford, A., Young, Y .L., Reilly, A. P., Bonin L. J., Rosman, R., Pathways for arsenic from sediments to groundwater to streams: Biogeochemical processes in the Inner Coastal Plain, New Jersey, USA, Water Research, 44, (19), pp. 5532-5544, 2010.
[6] Protić, I., Drašković, M., Jašin, D., Mikrobiološka kontrola vode za piće grada Zrenjanina, Zbornik radova sa 43. Međunarodne konferencije Vodovod i kanalizacija, Zrenjanin, str. 116-21, 2022, ISBN 978-86-80067-53-7.
[7] Pravilnik o higijenskoj ispravnosti vode za piće („Sl. list SRJ", br. 42/98 i 44/99 i „Sl.glasnik RS", br. 28/2019)
[8] Pravilnik o načinu uzimanja uzoraka i metodama za laboratorijsku analizu vode za piće. (Službeni list SFRJ br. 33/87).
[9] Council Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption ,Official Journal L 330 , 05/12/1998 P. 0032 – 0054.

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APPLICATION OF SUSTAINABLE FERTILIZERS: BIOCHAR AND PHOSPHATE GLASS EFFECTS AT ROSE FLOWERING

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Abstract:
Controlled release fertilizers (CRF) provide nutrients that dissolve gradually, remaining available to plants longer than conventional fertilizers. This study investigates the influence of phosphate glass and biochar, as prospective controlled-release fertilizers, on the growth and development of rose seedlings. Biochar is the product of thermochemical conversion of biomass, where organic substances are thermally broken down at specific process parameters, in a reduced oxygen atmosphere. Phosphate glass ($45.4P_2O_5 \cdot 25.6K_2O \cdot 14.5CaO \cdot 3.1SiO_2 \cdot 9.3MgO \cdot 1.2ZnO \cdot 0.9MnO$) was synthesized from reagent-grade materials by melting at 1230 °C for 1 h in a porcelain crucible and quenching on steel. Different dosages of plum stone biochar (PS) and phosphate glass (PG) were tested on rose plantings. The addition of PS and PG had no significant influence on the number of branches, but higher doses (3 g of PG and 10 g of PS) favored flower formation. Chemical analysis at the end of the cycle showed increased phosphorus and manganese in all samples, higher zinc with 2 g PG, and elevated calcium in all variants. Overall, addition of PG and PSB to the soil samples improved rose growth.
Key words: biochar, phosphate glass, CR fertilizers, roses.

INTRODUCTION

Flower production, as a specific form of agricultural production, is the most dynamic industry in the world and plays a significant role in economic and social development of any country. As a highly profitable sector, flower production is constantly growing, with an annual turnover exceeding 300 billion euros. Flowers have become the most fashionable consumer good, with great development potential, since the demand increases year by year (15–20% annually) alongside the rise in living standards. It is an industry that is „economically without borders" highly competitive and highly risky. It can be organized both in open fields and in protected environments. The flower industry is characterized by high investments, advanced technology, high returns, but also high risks [1-3].
In the era of significant environment pollution and nonrenewable resources depleting, researchers are constantly exploring for „new" fertilizers that ensure more effective action on crop growth, while having less impact on the environment. Biochar, a carbon-rich material produced by pyrolysis of biomass, has emerged as a sustainable soil amendment due to its multiple agronomic and environmental benefits. Its highly porous structure enhances soil aeration, water retention, liming potential, cation exchange capacity, but also brings significant content of available nutrients necessary for the plant growth. In addition, biochar addition often raises soil pH in acidic soils, creating more favorable conditions for plant growth [4, 5]. Biochar composition and structure has been proven as a valuable habitat for beneficial soil microorganisms, which further support nutrient cycling and plant health [6]. At the same time, many investigations have demonstrated ability of biochar to reduce the level of heavy metal contamination in soil and water, resulting in stimulated responses from microbial populations [7]. Many investigations worldwide are conducted in order to assess the benefits of biochar addition into the growing media of various horticultural and ornamental crops, [8], but all of them induce necessity of good biochar characterization and proper dosage onto the soil.

Agriglasses have in recent years been offered (and applied) as an alternative in flower production, as they have a positive effect both on the natural environment and on yields [9]. Their use provides the necessary nutrients in sufficient quantities that are easily accessible; they do not leach into deeper soil layers, since the unused portion of the glass remains in the upper layers of the soil, which also makes them environmentally justified. Agriglasses (glassy fertilizers) based on phosphate glasses are classified as a group of controlled-release (CR) fertilizers. Glassy fertilizers possess bioactivity, meaning they have the ability to participate in the biological processes of living organisms [10,11]. Phosphate glasses generally exhibit low chemical stability in aqueous solutions. The dissolution of the glass depends on the glass network itself as well as external factors, such as the condition of the glass surface, the ratio of glass surface area to solvent volume, saturation effects, the type of solvent, solvent flow rate, and others. Understanding the dissolution process and the rate of ion release from phosphate glasses in aqueous solutions is very important from the perspective of engineering material design [12]. The solubility of phosphate glasses can be tailored to specific plant types and soil conditions by modifying the chemical composition and granulation of the glass. During the plant growth cycle, the components released from the glass are consumed intensively, and their levels in the vicinity of the glass granules decrease, which increases the driving force of dissolution and intensifies the dissolution process. Conversely, at the end of the growth cycle, the consumption of the released components decreases, and their concentration around the glass granules increases, causing the driving force of dissolution to decrease and slowing down the glass dissolution process in the soil. Additionally, soil temperature and moisture have a significant effect on the glass dissolution process [13,14].
In this paper, we have investigated the effect of two "sustainable" fertilizers, agriglass and biochar, onto the rose flowering, in order to examine their possible effects and direct our future work. In the same time, chemical analyses of harvested rose plant biomass were performed in order to quantify the content of nutritional elements most important in the plant physiology: P, Zn, Ca and Mn.

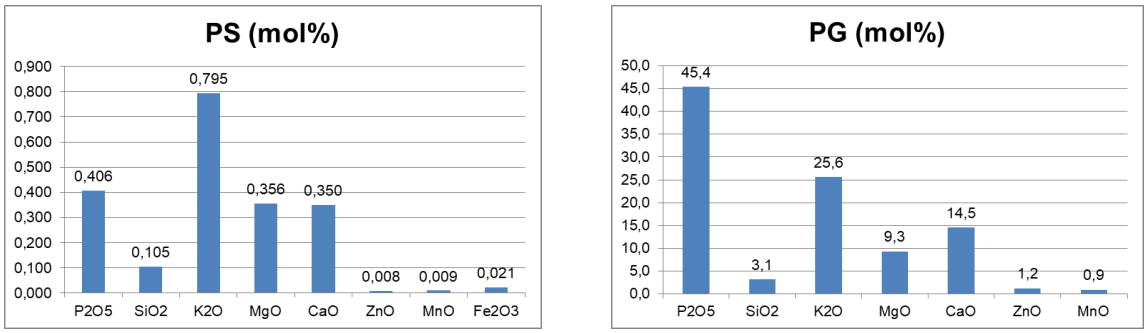
MATERIAL AND METHODS

Phosphate glass (PG) and plum stone biochar (PS) samples were synthesized as previously described in [15]. The chemical durability of PG and PS was assessed in 2% citric acid solution at 20 °C by the same methodology adopted from [15]. .The chemical composition of PG, PS, and the post-dissolution solutions was examined using gravimetric methods and spectroscopic techniques, including atomic absorption spectrometry (AAS; PERKIN ELMER AAnalyst 300) and UV–Vis spectrophotometry (Specol Analytik JENA 1300).
The *Lavaglut* rose cultivar was propagated via grafting in July 2022 within a two-year production cycle. The agronomic performance of PG and PS as eco-fertilizers was investigated beginning from February 15, 2023. Soil analysis revealed a neutral to slightly acidic reaction, an available nitrogen concentration of 32.9 mg/kg, low phosphorus availability, and sufficient potassium supply (22.4 mg/kg), conditions favorable for rose seedling cultivation [9]. PG was applied at three rates (1, 2, and 3 g/plant), whereas PS was tested at two rates (5 and 10 g/plant). Plant growth and developmental parameters were systematically recorded throughout the vegetative cycle. The counting of open flowers was conducted three times from late May to mid-September.
In mid-September, composite samples of aboveground roses biomass were collected from all experimental variants for chemical analysis of the rose plant material. The biomass (rose leaves with twigs) was dried in an oven at 60 °C and subsequently ground to achieve sample homogenization. The plant material was digested with concentrated HNO_3, followed by oxidation with concentrated $HClO_4$.
Elemental contents (K, Ca, Mg, Zn, Mn, and Fe) were determined by atomic absorption spectrophotometry using a Perkin Elmer 703 instrument, while phosphorus was quantified spectrophotometrically after extraction with isoamyl alcohol on a Spekol 1300 Jena spectrophotometer. Data analysis was conducted by one-way ANOVA (R software, v.3.6.0), with pairwise comparisons performed using Tukey's HSD test at a significance level of $p <$

0.05. Over the study period, six phytosanitary treatments were implemented to control diseases and pests.

RESULTS AND DISCUSSION

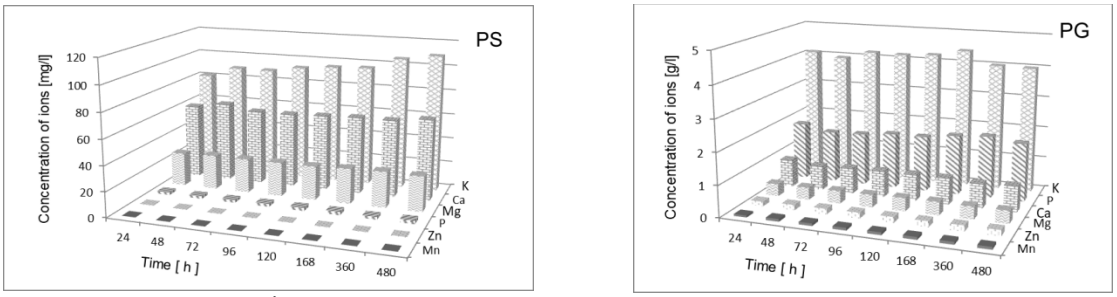
The chemical compositions of PS and PG employed in the experiments are summarized in Figure 1. The presented analyses primarily reflect the dominant mineral constituents within the samples, as the biochar matrix (Figure 1a) is largely carbonaceous (>70%), with mineral ash accounting for approximately 2% of the PS dry mass. In addition, PS biochar contains about 1.62% of nitrogen, an element of agronomic relevance due to its positive effect on plant growth [7]. Apart from the oxides presented in Figure 1, the PS sample also exhibited a minor Fe_2O_3 fraction (0.021%), which was absent in PG (Figure 1b).



a) b)

Fig. 1. *Chemical composition: a) biochar and b) phosphate glass.*

The investigated phosphate glass exhibits markedly lower chemical stability in citric acid solution compared to biochar. Over the longest experimental duration (480 h), approximately 98% of the glass dissolves, whereas only about 8% of the biochar undergoes dissolution within the same time frame. Figure 2 presents the ion concentrations in the solutions at various experimental intervals for biochar (Figure 2a) and for glass (Figure 2b). The ion concentrations are nearly 200-fold higher in the solutions resulting from glass dissolution than in those obtained from biochar.



a) b)

Fig. 2. *The ion concentrations in the solutions: a) biochar and b) phosphate glass.*

To evaluate the effects of phosphate glass and biochar as eco-fertilizers, the concentrations of elements absorbed by plants were determined in the plant material collected at the end of the vegetation period.

The results of the chemical analysis (Table 1) should be interpreted with caution due to the short duration of the study. These values are to be considered relative, as longer-term investigations (multi-year trials) are required to obtain reliable data. Only through extended experimentation can the consistent effects of phosphate glass and biochar application be confirmed, thereby providing a more accurate assessment of their agronomic potential.

Phosphorus is essential for the formation of cell membranes, carbohydrate metabolism, protein synthesis, photosynthesis, and the storage and transfer of energy. As emphasized by Mišić

[16], it strongly influences flower formation and plant growth. The application of phosphate glass and biochar (Table 1) resulted in an increase in phosphorus (P) content in all experimental variants compared to the control.

Table 1. *Macro- and microelement contents (mg/kg) in the analyzed rose plant material.*

Treatment variants	Ions [mg/kg]						
	P	K	Ca	Mg	Zn	Mn	Fe
Control	1929.91	9224.77	10249.75	3283.25	33.99	33.25	208.24
5 g PS	1970.77	7552.78	11749.40	3204.16	28.49	76.75	196.49
10 g PS	2630.07	8499.16	11498.85	3178.85	30.24	52.49	185.98
1 g PG	2065.71	8976.16	10251.30	3050.39	31.75	37.50	142.77
2 g PG	2131.68	8873.82	9748.72	3178.74	34.25	39.49	145.98
3 g PG	2003.38	7997.15	9746.50	3203.02	29.74	49.98	203.42

Manganese (Mn) is an important component of several enzymes. It also participates in various redox processes and contributes to plant resistance against abiotic and biotic stresses. The results obtained (Table 1) indicate that the content of this element was significantly higher in variants treated with all doses of phosphate glass and both doses of biochar compared to the control. The excess manganese can inhibit chlorophyll biosynthesis in leaves, which is reflected in the reduced Fe content in the plant material, showing a complete inverse correlation with Mn levels (higher Mn – lower Fe, and vice versa) [17].
Zinc (Zn), as an essential biogenic element, is involved in numerous plant functions and has been identified in more than 80 proteins [16]. This element is required for the synthesis of the amino acid tryptophan, which participates in auxin biosynthesis. The highest zinc content (Table 1) was recorded in the variant treated with 2 g of phosphate glass (34.25 mg/kg).
The calcium (Ca) ion content (Table 1), which serves as an important intracellular signal transducer and influences various developmental processes in plants, was increased compared to the control, particularly in the variants treated with both doses of biochar. Similar trend of elevated level of Ca content (but also decreased level of K) in rose biomass was observed by Fascella et al.[8] who investigated addition of biochar made from conifer wood as a substrate component for growing *Rosa rugosa* plants. These authors have also confirmed that in biochar applied pots plant leaves has a higher photosynthesis rate.
Regarding the contents of potassium (K), magnesium (Mg), and iron (Fe) in the plant material (Table 1), their highest levels were recorded in the control variant and showed correlations with the contents of other elements (higher calcium–lower magnesium, and vice versa).
The influence of various macro- and microelements on the development of rose seedlings can be assessed by observing the number of open flowers. Phosphorus is essential for the development of flower buds and the formation of flowers, and its deficiency reduces flower production. Calcium is important for the stability of cell membranes and intracellular signaling, affecting flower development and bud resilience. Zinc and manganese are critical for enzymatic processes and hormone-related pathways associated with flowering, such as auxin and gibberellin synthesis [18].
The counting of open flowers was conducted three times from late May to mid-September. Table 2 presents the results of all three counts of open rose flowers for all experimental variants.

Table 2. *Mean number of open flowers for each experimental variant*

Counting	Control	PS		PG		
		5 g	*10 g*	*1 g*	*2 g*	*3 g*
I	19c	19c	31a	19c	23b	18,5c
II	5c	3d	7a	3d	6b	7a
III	4a	2c	3b	2c	3b	4a

Different letters in the columns indicate a statistically significant difference between treatments at the 0.05 significance level.

The average number of flowers in the first count ranged from 19 (control, PS-5 g and PG-1 g), while the highest average number of flowers was recorded in variant PS-10 g. The average number of open flowers in the variant treated with 2 g of PG (23) was statistically significantly lower only compared to the average number of open flowers in variant PS-10 g, and statistically significantly higher than the average number of buds observed in all other variants.
During the second count, a positive effect of higher doses of PG (2 g and 3 g) as well as the higher dose of PS (10 g) on the average number of flowers formed was observed, which was statistically significantly higher compared to the average number of flowers in the control, variant PG-1 g, and variant PS-5 g. Furthermore, the application of 3 g of PG resulted in a statistically significant increase in the average number of flowers, even though it did not affect the average number of buds.
A similar trend was observed with biochar application, where the higher dose statistically significantly increased the average number of flowers compared to the lower dose.
During the third count, at the end of the growing season (mid-September), the average number of flowers was lower compared to the first and second counts. This is understandable, as roses enter a period of vegetative dormancy at the beginning of autumn. The highest average number of flowers (four) was recorded in the control variant and in the variant with the maximum tested dose of phosphate glass (3 g), and it was statistically significantly higher than the average number of flowers observed in all other experimental variants.
Plants primarily absorb available macro- and microelements from the soil, and when these sources are depleted, they begin to take up the same elements from applied fertilizers. Based on the results presented in Tables 1 and 2, it can be concluded that roses in all experimental variants absorbed higher amounts of phosphorus compared to the control, which positively affected the number of open flowers. Additionally, the amount of calcium absorbed by plants treated with phosphate glass was significantly higher than in the control, which may also contribute to an increased number of flowers. The manganese content was elevated in all plants treated with PG and PS compared to the control [18].

CONCLUSION

Besides bringing nutrients from depleting non-renewable sources, traditional water-soluble fertilizers may cause variety of environmental problems at the same time. Many papers have confirmed beneficial effects of new sort of slow-releasing fertilizers, which are able to improve the soil structure without its degradation, but also to enrich it by bringing essential nutrients necessary for plant growth. In this paper, we have confirmed beneficial effects of two environmental friendly fertilizers onto rose flowering: agriglass and biochar, both made in our laboratories. It is confirmed that, besides improving the ornamental quality of the roses grown (e.g. number of flowers), synthesized fertilizers brought essential microelements into the plant structure (P, Zn, Ca and Mn) improving overall plant health.

ACKNOWLEDGEMENT

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REFERENCES

[1] Thörning, R., Ahlklo, Å.K., Spendrup, S., The slow flower movement-exploring alternative sustainable cut-flower production in a Swedish context, Heliyon, Vol. 8, e11086, 2022.

[2] Karli, B., Songur, M., Sinek, B., Kadakoğlu, B., Economic Analysis of cut flower production (Carnation, Gerbera and Lisianthus) in Turkey: The case of Antalya Province, Economic Engineering in Agriculture and Rural Development, Vol. 22 [3], pp. 343-350, 2022.
[3] Đurić, K., Njegovan, Z., Ekonomika poljoprivrede, part 2 i 3, Univerzitet u Novom Sadu, Poljoprivredni fakultet, Novi Sad, 2016.
[4] Xu, G.; Lv, Y.; Sun, J.; Shao, H.; Wei, L., Recent Advances in Biochar Applications in Agricultural Soils: Benefits and Environmental Implications, Clean Soil Air Water, Vol. 40, pp. 1093–1098, 2012.
[5] Mu, L., Zhou, H., Wang, J., Sun, S., Yang, H., Zhang, N. and Bao, L., Effect of Modified Biochar with Organic Fertiliser on the Growth and Development of Chinese Rose, Advances in Bioscience and Biotechnology, Vol. 15, 344-359, 2024. doi: 10.4236/abb.2024.156021.
[6] Liu, Y., Zhu, J., Gao, W., Guo, Z., Xue, C., Pang, J., Shu, L., Effects of biochar amendment on bacterial and fungal communities in the reclaimed soil from a mining subsidence area, Environ. Sci. Pollut. R, Vol. 26, pp. 34368–34376, 2019.
[7] Joshua O. Ighalo, Chinemerem R. Ohoro, Victor E. Ojukwu, Mutiat Oniye, Wasim Akram Shaikh, Jayanta Kumar Biswas, Chandra Shekhar Seth, Ganesh Babu Malli Mohan, Sam Aldrin Chandran, Selvasembian Rangabhashiyam, Biochar for ameliorating soil fertility and microbial diversity: From production to action of the black gold, iScience, Vol. 28[1], art. No 111524, 2025.
[8] Fascella, G., Mammano, M. M., D'Angiolillo, F., & Rouphael, Y., Effects of conifer wood biochar as a substrate component on ornamental performance, photosynthetic activity, and mineral composition of potted Rosa rugosa, The Journal of Horticultural Science and Biotechnology, Vol. 93[5], pp. 519–528, 2017. https://doi.org/10.1080/14620316.2017.1407679
[9] Vujošević, A., Matijašević, S., Smiljanić, S., Nikolić, J., Zečević, B., Topalović, V., Savić, V., Polyphosphate glass as fertilizer for plant seedlings, Materials Protection, Vol. 60 [2], pp. 96–104, 2019.
[10] Mandal, B., Das, T., Hazra, G., Advanced controlled release glass fertilizer: An inner view, Journal of Emerging Technologies and Innovative Research, Vol. 5 [5], pp. 698-717, 2018.
[11] Labbilta, T., Ait-El-Mokhtar, M., Amine Harech, M., Anasser, I., Abouliatim, Y., Khouloud, M., Meddich, A., Mesnaoui, M., Advancing controlled-release phosphate glasses as sustainable fertilizers: Microelement-enhanced formulations and dissolution behavior analysis, Journal of Non-Crystlline Solids, Vol. 625, pp. 122765, 2024.
[12] Tošić, M.B., Nikolić, J.D., Grujić, S.R., Živanović, V.D., Zildžović, S.N., Matijašević, S.D., Ždrale, S. V., Dissolution behavior of a polyphosphate glass into an aqueous solution under static leaching conditions, Journal of Non-Crystalline Solids, Vol. 362 [1], pp. 185–194, 2013.
[13] Ouis, M. A., Abd-Eladi, M., Abou-Baker, N. H., Evaluation agriglass as an environment frendly slow release fertilizer, Silicon, Vol. 10 [2], pp. 293-299, 2018.
[14] Karapetyan, G., Karapetyan, K., Maksimov, L., Glassy environmentally frendly Fertilizers of prolonged action, Phosphorus Bulltin, Vol. 15, pp. 60-67, 2004.
[15] Topalović, V., Vujošević, A., Antanasković, A., Savić, V., Djošić, M., Lopičić, Z., Nikolić, J., Chemical stability and fertilizer efficiency of bioglass and biochar on rose plantings biochar on rose plantings, Proceedings of XVI International Mineral Processing and Recycling Conference, 2025, pp. 483-489
[16] Mišić, P., Jabuka, Nolit Beograd, 1994.
[17] Datta, S. K., Breeding of new ornamental varieties: Rose, Current Science, Vol. 114[6], pp. 1194-1206, 2018.
[18] Jayakumar, S., Abhangrao, A. K., Sarje, R. A., Gupta, R., Pathania, S., Sree, B. V., Critical analysis on effect of micronutrients on flowering plants: A Review, International Journal of Plant & Soil Science, Vol. 36[6], pp. 776-782, 2024.

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A MULTI-DIMENSIONAL APPROACH TO DANUBE RIVER PRESERVATION: COMBINING WATER QUALITY SCIENCE AND ACOUSTIC ART

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Abstract: This study presents an integrated environmental assessment of the Danube River at three sites near Novi Sad, Serbia, combining physicochemical water quality analysis with acoustic soundscape monitoring. Water samples collected at Burma Beach, Estuary DTD, and Resort Ribarsko Ostrvo in September 2024 were analyzed against Serbian and WHO standards. The results revealed overall high ecological status, with most parameters—including dissolved oxygen, nitrates, nitrites, and phosphorus—falling within Class I limits. However, localized exceedances in total organic carbon (TOC), ammonium, arsenic, and copper placed some samples in Class II and III, indicating moderate pressures from urban and industrial activities. Acoustic monitoring enriched the evaluation by capturing distinctive environmental soundscapes, from bird colonies and recreational noise to industrial ship traffic and underwater disturbances. These findings highlight the Danube's resilience while emphasizing the need for continuous monitoring to manage localized stressors. By combining scientific and sensory dimensions, this study demonstrates a novel interdisciplinary approach to river assessment and public environmental engagement.
Key words: Danube River, water quality, soundscape, Novi Sad, environmental monitoring

INTRODUCTION

Freshwater ecosystems provide essential services to human societies and natural biota, yet they are increasingly compromised by multiple, interacting anthropogenic pressures. Rivers are subject to nutrient enrichment from agricultural runoff, point-source discharges from industry and wastewater treatment plants, diffuse urban runoff, and physical disturbance from navigation and infrastructure development; together these stressors degrade water quality, alter biotic communities and reduce the capacity of rivers to supply safe water for drinking, recreation and ecosystem functioning [1,2]. The Danube — Europe's second-longest river and a transboundary corridor for commerce, industry and biodiversity — exemplifies these challenges because pollutants and hydromorphological pressures originating in one country propagate downstream across national borders, complicating management and remediation efforts [3].

Contemporary policy frameworks such as the European Union Water Framework Directive (WFD) require systematic monitoring and classification of ecological status to support integrated river basin management and to guide restoration measures [4]. Compliance with WFD objectives depends on robust, temporally and spatially representative data for key physicochemical and biological indicators. In parallel, there is growing recognition that non-chemical dimensions of rivers — notably their acoustic environments or "soundscapes" — convey valuable information about anthropogenic activity, habitat condition and the presence or absence of fauna; acoustic monitoring can thus complement conventional monitoring by revealing patterns of disturbance (e.g., shipping and recreational noise), biotic activity (e.g., bird and fish sounds) and human–environment interactions that are not captured by chemical analyses alone [5].

The present study adopts an interdisciplinary perspective by combining targeted physicochemical water quality assessment with systematic acoustic observations at three sites

adjacent to Novi Sad, Serbia (Burma Beach — NS3, Estuary DTD — NS2, and Resort Ribarsko Ostrvo — NS1). Field sampling and acoustic recordings were conducted in September 2024. The objectives were: (i) to evaluate local ecological status against national (Serbian) and international (WHO/EU) criteria for selected water quality parameters; (ii) to characterise site-specific soundscapes and identify predominant natural and anthropogenic acoustic signatures; and (iii) to integrate these datasets in order to enhance interpretation of environmental pressures and inform localized management and communication strategies. By coupling conventional laboratory analyses with sensory and contextual information derived from soundscape data, the study aims to provide a more nuanced appraisal of river condition and to demonstrate the utility of multidimensional monitoring approaches for riverine conservation and public engagement.

MATERIAL AND METHODS

Study Sites

Field investigations were carried out in September 2024 at three representative locations along the Danube River within the urban area of Novi Sad, Serbia (Fig.1). The sites were selected to capture a gradient of anthropogenic pressures ranging from recreational to industrial activities:

- Burma Beach (NS3): A semi-recreational site located downstream of the city, frequently used for bathing and leisure activities during summer months. At the time of sampling, ongoing construction activities in the vicinity, together with episodic waste disposal, represented potential sources of localized disturbance.
- Estuary of the Danube–Tisza–Danube (DTD) Canal (NS2): Situated at the confluence of the artificial canal network with the Danube, this site is strongly influenced by navigation, shipping activities, and intensive anthropogenic inputs. Floating litter and traces of oil films were visibly present at the water surface during fieldwork.
- Resort Ribarsko Ostrvo (NS1): A popular recreational and tourist area positioned close to a major traffic bridge. This site experiences continuous acoustic disturbance from road traffic, but hydrological conditions are relatively stable due to its distance from industrial discharge points.

Together, these sites provide a useful basis for evaluating how different land-use types and anthropogenic activities affect both the chemical status and the acoustic environment of the river.

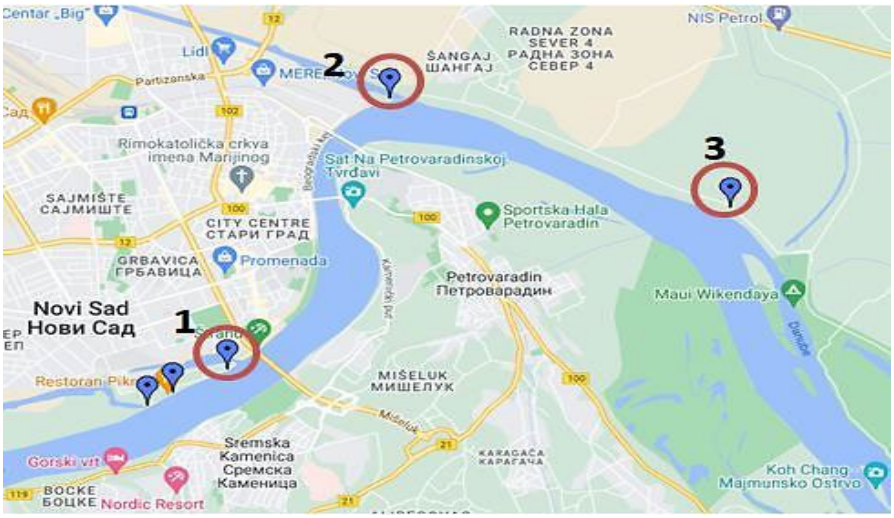


Fig. 1. *Map of the sampling sites*

Water Quality Analysis

Water samples were collected in pre-cleaned polyethylene bottles at a depth of approximately 0.5 m, stored under refrigerated conditions, and transported to the laboratory within 24 hours for analysis. Analytical procedures followed standard protocols defined by Serbian national regulations on surface water quality [6] and were cross-referenced with World Health Organization (WHO) drinking water guidelines [1] to ensure comparability with international standards.
The following physicochemical parameters were measured:

- Dissolved oxygen (DO): Winkler titration method;
- Biochemical oxygen demand (BOD_5): Five-day incubation at 20 °C;
- Nutrients: Nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), and total phosphorus (TP) were quantified using spectrophotometric methods after appropriate sample preparation;
- Organic load indicators: Total organic carbon (TOC) determined by high-temperature catalytic combustion;
- Heavy metals (As, Cu, Pb, Ni, Cd): Measured by inductively coupled plasma–mass spectrometry (ICP–MS) following acid digestion.

All analyses were conducted in triplicate to ensure accuracy and reproducibility. Results were evaluated against Serbian surface water quality classes (I–V) and compared with WHO recommended thresholds.

Acoustic Monitoring

To complement water quality analysis, a systematic program of acoustic monitoring was implemented at each site. Recordings were conducted using a dual-channel setup consisting of a calibrated hydrophone (sensitivity: –164 dB re 1 V/µPa, frequency response: 20 Hz–20 kHz) and an omnidirectional ambient microphone (frequency response: 20 Hz–20 kHz, positioned at 1.5 m height). Each recording session lasted 15 minutes, performed under stable meteorological and hydrological conditions to ensure comparability.
Recordings were processed using specialized software (e.g., Raven Pro, Audacity) to generate spectrograms and frequency distributions. Key acoustic parameters included:

- Sound Pressure Level (SPL, dB re 1 µPa underwater / dB(A) in air): quantifying the intensity of sound at different frequency bands.
- Frequency composition: separating low-frequency (<500 Hz, typically associated with shipping and construction) from mid-to-high frequencies (>1 kHz, often related to bird vocalizations or recreational activity).
- Temporal variability: distinguishing continuous (traffic, ship engines) from intermittent signals (bird calls, short machinery bursts).

This approach enabled both qualitative identification of dominant sound sources and quantitative assessment of their intensity and variability. By integrating these findings with water quality data, a more comprehensive picture of anthropogenic pressures on the river ecosystem was obtained.

RESULTS AND DISCUSSION

Water Quality

The overall results indicate that the Danube River in the Novi Sad region maintains a generally good ecological status, but with localized signs of anthropogenic stress (Table 1). Across all sites, concentrations of dissolved oxygen (DO) remained within Class I limits, reflecting favorable conditions for aquatic life and efficient self-purification capacity. Similarly, nitrate and nitrite levels were consistently low, suggesting that nutrient enrichment was not a dominant pressure at the time of sampling. These findings are consistent with earlier studies on the Serbian stretch of the Danube, which also reported relatively stable oxygen conditions and moderate nutrient concentrations under non-flood conditions [7,8].
However, several parameters revealed site-specific exceedances that lowered the ecological classification from Class I to Class II or III. Total organic carbon (TOC) values exceeded Class I thresholds at all three sites, highlighting the influence of urban runoff, organic discharges, and intensive human use of the river. Elevated ammonium was detected at NS3 (Burma Beach), likely linked to both untreated wastewater inputs and seasonal recreational pressures. At NS2 (Estuary DTD), concentrations of arsenic and copper exceeded Class II limits, pointing to inputs from shipping activities and industrial runoff transported via the canal system. In contrast, NS1 (Ribarsko Ostrvo) displayed relatively stable conditions, with exceedances limited to TOC. Importantly, concentrations of cadmium, nickel, and lead remained below national and WHO thresholds at all sites, indicating no acute heavy metal contamination at the time of sampling.
These localized deviations from high ecological status are consistent with broader basin-wide assessments such as the Joint Danube Survey, which has repeatedly identified urban centers and canal confluences as hotspots for organic and trace metal pollution [9].

Table 1. *Results of physico-chemical analysis of Danube River water*

Parameter	Unit	Determined Value			Guideline Value[1]	Thresholds[2]				
		Burma Beach	Estuary DTD	Ribarsko		Class 1	Class 2	Class 3	Class 4	Class 5
Dissolved Oxygen	mg-O_2/L	9.2	9.7	9.9	-	>8.5	7	5	4	<4
Nitrates	mg-N/L	1.1	1.1	1.1	50 mg/L	1-1.5	3	6	15	>15
Nitrites	mg-N/L	0.014	0.026	0.008	3 mg/L	0.01	0.03	0.12	0.3	>0.3
Ammonium	mg-N/L	0.3	0.29	0.1	*Not established but natural levels usually below 0.2 mg/L	0.1 – 0.05	0.1 – 0.3	0,6	1.5	>1.5
Lead	µg/L	2.2	9.8	2.3	10 µg/L	-				
Cadmium	µg/L	0.3	0.6	0.3	3 µg/L	-				
Copper	µg/L	3.,2	9.8	1.9	2 µg/L	5	5	500	1000	>1000
Arsenic	µg/L	2.8	6.1	1.4	10 µg/L	<5	10	50	100	>100
Total Chromium	µg/L	0.5	13.3	1.4	-	-				
Total Phosphorus	mg-P/L	<0.04	<0.04	<0.04	-	0.05	0.2	0.4	1	>1
Sodium	mg/L	11.3	11.4	11	*Not established but natural levels usually below 20 mg/L	-				
Biological Oxygen Demand (BOD_5)	mg-O_2/L	1.5	2.5	1.3	-	1.8 – 2.0	4.5 – 5.0	7	25	>25
Potassium	mg/L	<2	2.5	2.4	-	-				
Nickel	µg/L	<2	18.8	5.6	70 µg/L	-				
Calcium	mg/L	48.3	48.2	48.1	-	-				
Magnesium	mg/L	12.3	12.4	12.4	-	-				
Total Organic Carbon TOC	mg/L	3.7	3.6	3.6	-	2	5	15	50	>50

[1] *World Health Organization (WHO). (2017). Guidelines for drinking-water quality: Fourth edition incorporating the first addendum.*
[2] *Official Gazette of the Republic of Serbia, No. 50. (2012, May 18) – "Regulations on limit values of polluting substances in surface and underground waters and sediment and deadlines for reaching them"*

Acoustic Soundscapes

Soundscape analysis revealed pronounced differences among the three study sites, reflecting both their geographical context and dominant human activities.

- NS3 (Burma Beach): Recordings captured a mixture of natural and anthropogenic sounds. Bird colonies were particularly prominent, contributing positively to the ecological acoustic signature. However, background construction noise was consistently present, and underwater recordings showed intermittent low-frequency disturbances likely linked to nearby machinery.
- NS2 (Estuary DTD): This site was dominated by anthropogenic acoustic activity. Ship engines, propeller turbulence, and radio frequency interference were the most distinctive sound sources. Such noise pollution has been reported in other navigational hotspots along the Danube [10], where it poses risks for aquatic fauna, particularly fish species sensitive to low-frequency vibrations.
- NS1 (Ribarsko Ostrvo): Above-water recordings were strongly influenced by continuous traffic noise from the adjacent bridge, overshadowing natural sound signals. In contrast, underwater recordings showed more stable soundscapes, with relatively weak anthropogenic interference. This suggests that while air-borne noise may impact human recreation and bird habitats, underwater ecosystems at this site remain less disturbed acoustically.

The integration of acoustic data provides an additional interpretative layer beyond chemical analysis. For example, NS2 showed both higher chemical stress (TOC, metals) and strong acoustic disturbance, underscoring its role as a critical pressure point. NS1, by contrast, appeared chemically stable but acoustically stressed by traffic. This highlights the importance of combining multiple monitoring approaches to fully understand ecological dynamics. Moreover, the recorded soundscapes from each Novi Sad location are publicly accessible on the official STREAM project platform (https://stream.democratia-aqua.org), while a visual representation of the acoustic profiles is presented in Figure 2.

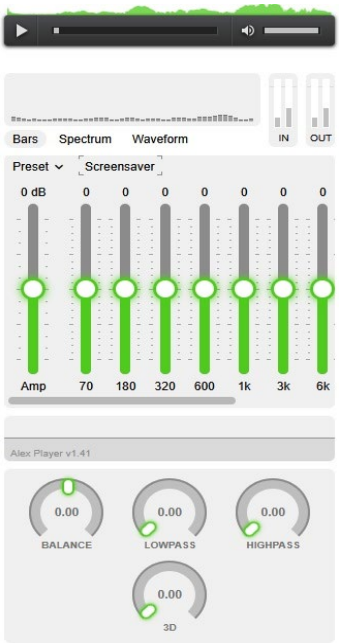


Fig.2. *Soundscape Danube recording*

Comparative Context

The observed patterns align with findings from previous Serbian studies. Milovanović [8] identified elevated organic load and trace metals near canal confluences, particularly in urban sectors, while Liška et al. [9] documented shipping corridors as noise and contamination hotspots along the middle Danube. Recent research on river soundscapes has similarly shown that anthropogenic noise can mask biological signals and interfere with ecosystem functioning [11]. By integrating chemical and acoustic indicators, the present study provides a more nuanced understanding of localized pressures in a highly urbanized stretch of the Danube.

Implications for Monitoring and Management

The results emphasize that while the Danube near Novi Sad generally complies with high water quality standards, localized stressors—particularly organic pollution, trace metals at the canal estuary, and continuous noise inputs—require targeted management. The findings suggest three key implications:

1. Enhanced monitoring frequency at NS2, where canal inputs significantly affect water quality.
2. Mitigation of organic load through improved wastewater management and stormwater treatment in urban zones.
3. Integration of acoustic monitoring into regular environmental assessments, not only to capture ecological stress but also to raise public awareness of river soundscapes as cultural and environmental assets.

Such multidimensional monitoring aligns with EU strategies for holistic water management and could be further expanded by incorporating biological indicators (e.g., benthic invertebrates, fish surveys) in future studies.

CONCLUSIONS

This study demonstrates that the Danube River near Novi Sad maintains generally good ecological conditions, with most physicochemical parameters falling within Class I limits. Nevertheless, localized exceedances of TOC, ammonium, arsenic, and copper indicate the presence of moderate pressures, particularly at the Estuary DTD (NS2) and Burma Beach (NS3). These results are consistent with previous reports identifying canal confluences and urban zones as hotspots for organic and trace metal pollution along the Danube.

Acoustic monitoring revealed site-specific soundscapes that enriched interpretation of chemical data. While NS1 (Ribarsko Ostrvo) appeared chemically stable but acoustically affected by continuous traffic, NS2 combined both chemical stress and intensive shipping-related noise, reinforcing its role as a critical pressure zone. Such findings underscore the importance of integrating sensory dimensions into water quality assessments, as they capture environmental disturbances that may otherwise remain undetected.

Overall, the combination of physicochemical and acoustic approaches provided a multidimensional understanding of river conditions in an urbanized setting. This methodological framework can support more effective environmental monitoring, communication with stakeholders, and awareness-raising among the public. Future research should build on these findings by incorporating biological indicators and long-term monitoring to further enhance sustainable management of the Danube in Serbia.

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REFERENCES

[1] World Health Organization (WHO). Guidelines for Drinking-Water Quality, 4th ed. WHO, Geneva, 2017.
[2] Vörösmarty, C. J., et al. "Global threats to human water security and river biodiversity." Nature 467, 555–561 (2010), https://www.nature.com/articles/nature09440.
[3] Somlyódy, L. "Water quality management in the Danube Basin." Water Science and Technology 38(11), 11–20 (1998), https://doi.org/10.1016/S0273-1223(98)00765-1.
[4] European Parliament and Council. Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for Community action in the field of water policy. Official Journal of the European Communities, 2000
[5] Krause, B. "The niche hypothesis: A hidden symphony of animal sounds, the origins of musical expression and the health of habitats." Soundscape Newsletter 16, 6–10 (1998).
[6] Official Gazette of the Republic of Serbia, No. 50/2012. Regulations on Limit Values of Polluting Substances in Surface and Groundwater.
[7] Milovanović, M. "Water quality assessment and determination of pollution sources along the Danube River in Serbia." Desalination 213, 159–173 (2007), https://doi.org/10.1016/j.desal.2006.06.022.
[8] Radovanović, M., Popović, B., & Štambuk-Giljanović, N. Water quality of the Danube in Serbia: Long-term trends and spatial variations. Environmental Monitoring and Assessment, 192, 623 (2020). https://doi.org/10.1007/s10661-020-08610-5
[9] Liška, I., Wagner, F., & Sengl, M. (eds.). Joint Danube Survey 3: A Comprehensive Analysis of Danube Water Quality. ICPDR, Vienna, 2015.
[10] Wysocki, L. E., Dittami, J. P., & Ladich, F. Ship noise and cortisol secretion in European freshwater fishes. Biological Conservation, 128(4), 501–508 (2006). https://doi.org/10.1016/j.biocon.2005.10.020
[11] Gandy, M. "The acoustic ecology of urban infrastructure." New Formations 78(78), 15–33 (2013). https://doi.org/10.3898/newf.78.02.2013

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READING BETWEEN THE WASTE: CORRELATION ANALYSIS OF INORGANIC POLLUTION IN LANDFILLS

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Abstract: Landfills represent one of the most prevalent sources of inorganic pollution, with leachates carrying a complex mixture of dissolved ions and trace elements that can migrate into surrounding soils and groundwater. Understanding the relationships among these contaminants is crucial for evaluating environmental risks and designing effective monitoring strategies. Collected leachate samples stem from a landfill in northern Serbia and were analyzed for a range of inorganic parameters. Using the Spearman rank correlation analysis, it was confirmed that there are four strong positive correlations between different parameters (Chemical Oxygen Demand/Total Kjeldahl Nitrogen, Total Kjeldahl Nitrogen/Ammonia Nitrogen, Chemical Oxygen Demand/Chromium and Chromium/Total Kjeldahl Nitrogen). Furthermore, there were two moderate positive correlations (Total Dissolved Solids/Total Kjeldahl Nitrogen and Nickel/ Chemical Oxygen Demand). These correlations provide additional insight into secondary interactions, dilution effects, and environmental transformations happening within the landfill body. This research emphasizes the value of statistical approaches in environmental assessment, where the showcasing and interpretation of links between pollutants can be used to support sustainable waste management and protection of water resources.
Keywords: statistical assessment, leachate quality, inorganic indicators, environmental monitoring

INTRODUCTION

In most developing countries, landfill deposition represents the principal approach to municipal solid waste management. A major drawback of this type of waste management is that the infiltration of rainwater through the landfill produces a highly polluted effluent loaded with organic and inorganic substances [1, 2, 3]. A combination of microbial, chemical, and physical processes within the landfill matrix facilitates the transfer of contaminants from municipal solid waste into percolating or infiltrating water. Most landfill receives a great amount of municipal, commercial, as well as mixed industrial waste all together disposed of in one place. They all contribute to forming significant amounts of leachates as well as the contamination of groundwater [4]. The production of the leachate is an important environmental problem.

The quantity and quality of leachate generated from landfills are influenced by numerous interacting factors, including annual precipitation, runoff, infiltration, evaporation, transpiration, ambient temperature, waste composition and density, initial moisture content, and landfill depth [5, 6, 7, 8, 9]. It is imperative to consider these factors when assessing the potential environmental risks associated with landfills and designing appropriate mitigation measures. The characteristics of the leachate also depend on the pre-treatment of the solid waste, such as separation of recyclable materials (such as plastics, paper, metals, glass, etc.), shredding and/or bailing of the waste. However, it always has a high content of suspended and dissolved matter, which makes it a dangerous pollutant that needs to be treated. Additionally, it has the potential to contaminate aquifers, rivers, and soil, posing risk to natural ecosystems, and public health [5].

This study aimed to enhance the understanding of the links between the various inorganic parameters in landfill leachate, focusing on exemplary landfills located in Vojvodina region. The findings will provide valuable insights into chemical mechanisms within the landfill body, which ultimately will serve as a guide to future monitoring programs related to unsanitary landfills and their impact on the environment and surrounding population.

MATERIAL AND METHODS

Sampling and analysis

The Novi Sad landfill, a controlled yet non-sanitary landfill, began operations in 1983 and is situated in the northern region of Novi Sad, Serbia. It is located 800 meters away from the nearest residential area and 7 kilometers away from the city center. Waste disposal is divided into three sections on the site. Though the landfill is controlled, it lacks a leachate collection system. The leachate sampling was conducted from a peripheral canal (S1: 45°18'39.33", 19°50'43.25", Figure 1a) and leachate lagoon (S2: 45°18'45.65", 19°50'54.40", Figure 1b). To account for seasonal variation, three sampling campaigns were conducted in 2022, specifically in February, May, and November, resulting in the collection of a total of 6 representative samples.

1a) **1b)**



Fig. 1. *Sampling locations in Novi Sad (1a – peripheral canal, 1b – leachate lagoon)*

Determination of physico-chemical indicators

All physicochemical analysis were carried out in the Laboratory for Environmental and Occupational Monitoring, Department of Environmental Engineering and Occupational Safety and Health, Faculty of Technical Sciences, University of Novi Sad**.** For the purposes of this study, the parameters that were examined were: chemical oxygen demand (COD), biological oxygen demand (BOD_5), BOD_5/COD ratio, Total Kjeldahl Nitrogen (TKN) and ammonia nitrogen (AN) and seven heavy metals: hexavalent chromium (Cr^{6+}), iron (Fe), zinc (Zn), nickel (Ni), lead (Pb), manganese (Mn), and copper (Cu). The physico-chemical parameters were determined utilizing standard laboratory EPA and HACH procedures.

Spearman rank correlation

The Spearman correlation is a non-parametric measure of rank correlation that assesses how well the relationship between two variables can be described using a monotonic function. A monotonic relationship is one where the variables tend to change together, but not necessarily at a constant rate. It can be used for relationships that are linear or non-linear [10]. The Spearman correlation coefficient, denoted as ρ, ranges from -1 to 1:

- ρ = 1: Perfect positive monotonic relationship.
- ρ = −1: Perfect negative monotonic relationship.
- ρ = 0: No monotonic relationship.

The IBM SPSS program was employed to determine the strength of the correlation among the examined parameters.

RESULTS AND DISCUSSION

Inorganic parameters

Selected parameters of interest for leachate characterization are shown in Table 1 and 2. In addition, as an important parameter for estimation of leachate biodegradability level, BOD_5/COD ratio was determined. The lead (Pb) concentrations in the examined samples have been determined to be beyond the limit of detection.

Table 1. *Physico-chemical parameters of analyzed leachate*

Landfill	Month	Parameter				
		COD (mg/L)	BOD_5 (mg/L)	BOD_5/COD ratio (/)	TKN (mg/L)	AN (mg/L)
S1	February	280	170	0.61	64.18	41.15
	May	310	142	0.46	60.38	36.49
	November	310	140	0.45	98.09	51.09
S2	February	1488	354	0.24	560.42	424.74
	May	1234	372	0.30	157.92	95.51
	November	670	170	0.25	61.81	33.62

Table 2. *Heavy metal contamination of analyzed leachate*

Landfill	Month	Parameter						
		Cr^{6+} (mg/L)	Fe (mg/L)	Zn (mg/L)	Ni (mg/L)	Pb (mg/L)	Mn (mg/L)	Cu (mg/L)
S1	February	0.03	1.10	0.41	2.42	<1	0.08	0.43
	May	0.12	27.98	0.37	2.49	<1	0.35	0.03
	November	0.08	6.63	0.26	2.56	<1	0.11	0.36
S2	February	0.38	2.78	0.32	2.53	<1	0.30	0.04
	May	0.15	5.98	0.29	2.55	<1	0.61	0.01
	November	0.25	3.74	0.38	2.51	<1	0.28	0.05

The parameter that showcases the biodegradability, BOD_5, is largely dependent on the leachate's maturity, which diminishes over time [9]. These results further confirmed the correlation reported by Bhambore and Kumar [9], as S1 and S2 exhibited very low BOD_5 values, consistent with the landfill's 40-year age. Another parameter highly influenced by the age of landfill is COD, as the susceptibility of waste to biological and chemical degradation processes decreases with time [11]. In terms of COD the average leachate characteristics reported from this research were typical for mature landfills with values <4000 mg/L, which align with the findings reported by Teng et al. [12]. Similar COD values are reported for examined landfills in conducted studies by Wdowczyk and Szymanska-Pulikowska [11]. The transitional phase of a landfill occurs when the ratio of BOD_5/COD is in the range 0.1-0.4 [13]. However, since the BOD_5/COD ratio is above >0.1 for S1 and S2, moderate biodegradability can be considered according to Bhambore and Kumar [9]. As stated in Table 1, maximum concentrations of AN were recorded for S1 (51.09 mg/L) and S2 (424.74) during the November and February camping, respectively. This trend was also observed for TKN values (98.09 and 560 mg/L for S1 and S2, respectively). It is scientifically established that AN does not depend on landfill age and is chemically stable, posing a problem for future landfill water treatment technologies based on microbial decomposition. Due to its high nitrogen content, food waste is the main source of AN amounts that are considered substantial. AN may threaten aquatic life if it exceeds the maximum allowable concentration [14].

The fluctuation in metal contents may be attributed to the waste's high heterogeneity and the increased solubility of metals due to the biological production of organic (fatty) acids resulting from the continuous deposition of fresh waste. Older landfills typically have low metal concentrations due to adsorption and/or precipitation reactions with co-existing sulfide, hydroxide ions, or carbonate. Leaching of heavy metals is affected by complexation, adsorption and desorption processes [15]. In this study, the highest Fe concentrations were observed at 27.98 mg/L (S1). A study by Sanga et al. [16] reported higher Fe concentrations than in our research, with a range from 72.00 - 625.00 mg/L, which were attributed to the disposal of steel objects at landfill sites. Furthermore, high levels of Fe in the leachate may result from the presence of construction materials, paints, dyes, solvents, polishing agents, and electrical equipment in the waste, which are recognized as primary sources of iron in landfill leachate [11]. The range of Cu values of the studied leachates were in accordance with typical copper values in landfill leachate reported by Gupta et al. [17] (0.306 and 0.199 mg/L) and Sanga et al. [15] (<0.01 and 0.80 mg/L). It is suspected that these concentrations may indicate the presence of items such as light bulbs, batteries, used engine oils, varnishes, or pharmaceuticals that were not selectively collected during landfill operation, as found by Wdowczyk and Szymanska-Pulikowska [11]. Nickel (Ni) concentrations at landfill sites were relatively high, with maximum values of 2.56 mg/L (S1) and 2.55 mg/L (S2). High values of nickel found in the present research most likely indicate the disposal of old batteries, which highly contributed to Ni values. Anthropogenic sources of zinc in soils typically include discharges from smelter slags and wastes, mine tailings, coal and fly ash residues, as well as the application of commercial products such as fertilizers and wood preservatives containing zinc [18]. Since leachate permeates the soil, it is expected that these Zn concentrations are also influenced by the soil around the landfill site. Likewise, the Cr values found in the studied leachate are highly likely due to the presence of consumer products like wood treated with copper dichromate, leather tanned with chromic sulfate, and stainless steel cookware. Manganese was found in concentrations below 1 mg/L. Hagelstein [19] listed the nonferrous applications of manganese which included the production of dry-cell batteries, plant fertilizer components, animal feed and colorant for bricks, dry cell batteries and as a black-brown pigment in paint.

Spearman rank correlation

Several statistically significant correlations were detected in the leachate samples. COD was found to be strongly associated with TKN (0.836) and with AN (0.816). This means that as COD values increase, nitrogen compound concentrations tend to rise in parallel. Such relationships are important because COD, TKN, and AN are commonly used indicators of leachate pollution, especially with respect to organic matter. Elevated COD values point to a greater presence of degradable organic substances, while TKN incorporates both inorganic and organic nitrogen fractions. Taken together, these results indicate that the breakdown of organic waste material is a major source of nitrogen release into the leachate. Among all tested parameters, the strongest positive relationship occurred between TKN and AN, with a correlation coefficient of 0.880. COD also exhibited a high correlation with chromium (0.845), suggesting that chromium present in waste items, such as certain industrial products or household materials, can migrate into the leachate. Chromium was further linked to TKN, with a coefficient of 0.837. Moderate correlations were also observed. Nickel also showed a moderate positive correlation with COD (0.643). The presence of Ni is probably related to the disposal of spent batteries, which is more common in non-sanitary landfills. The results provide a clearer understanding of pollutant dynamics across different landfill conditions.

CONCLUSION

This research provides a comprehensive overview of inorganic pollutants present in landfill leachate, which, in the absence of well-established or effective landfill management practices, are released into the surrounding environment. The Spearman rank correlation analysis for the selected Serbian landfill was conducted, yielding four very strong correlations. These results emphasize the complexity of landfill leachate composition and reveal the strong interactions among the examined parameters. Such findings can serve as valuable evidence to guide governmental and regulatory bodies in strengthening waste management policies and implementing more effective pollution control strategies for these toxic sources.

The persistence of these contaminants, coupled with their widespread use in consumer products, underscores the urgency for stricter regulatory measures and the development of innovative strategies aimed at reducing their release into surrounding ecosystems. Furthermore, the study reinforces the necessity of establishing proper leachate collection systems and treatment facilities, as well as the broader benefits of comprehensive waste management programs.

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REFERENCES

[1] Mausam K.P., Mithra D., Chandra S. Impact of Open Dumping Site on Groundwater Quality in Silchar City, Assam, India. Water, Air and Soil Pollution 235:659, 2024.

[2] Luo H., Zeng Y., Cheng Y., He D. and Pan X. Recent advances in municipal landfill leachate: a review focusing on its characteristics, treatment, and toxicity assessment. Science of The Total Environment, Vol 703:135468, 2020.

[3] Detho A., Kadir A. A., Zawani Z.I.B. Heavy Metal Characteristics of Soil and Leachate Resistivity Mapping of Malacca Landfill, Water, Air and Soil Pollution 235:115, 2024.

[4] Abdel-Shafy, H. I., Amr, M. I., Al-Sulaiman, A. M., Okasha, R. A. Landfill leachate: Sources, nature, organic composition, and treatment: An environmental overview. Ain Shams Engineering Journal 15, 102293, 2024.

[5] Keyikoglu R., Karatas O., Rezania H., Kobya M., Vatanpour V. and Khataee A. A review on treatment of membrane concentrates generated from landfill leachate treatment processes. Separation and Purification Technology 259:118182, 2021.

[6] Kumar D., Alappat B.J. Analysis of Leachate Contamination Potential of a Municipal Landfill using Leachate Pollution Index. Workshop on Sustainable Landfill Management 3–5 December, 2003; Chennai, India, pp. 147-153, 2023.

[7] Wijekoon P., Koliyabandara P.A., Cooray A.T., Lam S.S., Athapattu B.C.L., Vithanage M. Progress and prospects in mitigation of landfill leachate pollution: Risk, pollution potential, treatment and challenges. Journal of Hazardous Materials 421:126627, 2022.

[8] Chaudhary R., Nain P., Kumar A. Temporal variation of leachate pollution index of Indian landfill sites and associated human health risk. Environmental Science and Pollution Research, 2021.
[9] Bhambore N., Kumar M.S. Assessing seasonal fluctuations in leachate chemical properties and leachate pollution index as contamination indicators. Environmental Monitoring Assessment 195:1432, 2023.
[10] Montgomery D.C., Runger G.C. Applied statistics and probability for engineers 3rd edition. Published by John Wiley & Sons, Inc, 2020.
[11] Wdowczyk A., Szymanska-Pulikowska A. Analysis of the possibility of conducting a comprehensive assessment of landfill leachate contamination using physicochemical indicators and toxicity test. *Ecotoxicology and Environmental Safety 221*:112434, 2021.
[12] Teng C., Zhou K., Peng C., Chen W. Characterization and treatment of landfill leachate: a review. *Water Research 203*:117525, 2021.
[13] Podlasek A., Vaverkova M.D., Koda E., Jakimiuk A., Martínez Barroso P. Characteristics and pollution potential of leachate from municipal solid waste landfills: Practical examples from Poland and the Czech Republic and a comprehensive evaluation in a global context. *Journal of Environmental Management 332*:117328, 2023.
[14] Wae AbdulKadir W.A.F., Omar R.C, Sharafee Shamsudin, M. Ammoniacal nitrogen – A critical contaminant in leachate composition: Characteristics, potential risk, and adsorption treatment innovations. Journal of Water Process Engineering 62, pp. 105424, 2024.
[15] Weihua L., Kai G., Qianwen Y., Yingjie S., Yan W., Mingxue X., Rongxing B., Huawei W., Ya-nan W., Dalei Z. Leaching behavior and environmental risk assessment of toxic metals in municipal solid waste incineration fly ash exposed to mature landfill leachate environment. *Waste Management 120*, pp:68-75, 2021.
[16] Sanga V.F., Fabian C. Kimbokota F. Heavy metal pollution in leachates and its impacts on the quality of groundwater resources around Iringa municipal solid waste dumpsite. *Environmental Science and Pollution Research 30*:8110-8122, 2023.
[17] Gupta S., Nandimandalam J.R. Potential environmental pollution study by leachate generation and health risk assessment in the vicinity of bandhwari landfill disposal site, National Capital Region, India. *Groundwater for Sustainable Development 23*:101032, 2023.
[18] Xu D. The mechanistic insights into the leaching behaviors of potentially toxic elements from the indigenous zinc smelting slags under the slag dumping site scenario. *Journal of Hazardous Materials Volume 437*:129368, 2022.
[19] Hagelstein K. Globally sustainable manganese metal production and use. Journal of *Environmental Management 90*, pp: 3736–3740, 2009.

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BIOPLASTICS AND THEIR BIODEGRADATION IN NATURAL ENVIRONMENTS

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Abstract: Bioplastics are kind of plastics produce from natural and renewable raw materials biomass sources such as sugarcane, corn starch, wood, waste paper, vegetable oils and fats, bacteria, algae, etc. As an alternative to conventional petrochemical plastics, bioplastics are naturally degraded in the environment, and are not harmful to nature environment because it can decompose back into carbon dioxide. Thus, the products made from bioplastics are renewable, biodegradable, compostable and environmentally friendly. The aims of this short review are to present classifications of bioplastic, their advantages and disadvantages, processing, applications and the process of biodegradation.
Key words: bioplastic, biodegradation, environment

INTRODUCTION

Plastic is considered the most useful material during the last century, playing a fundamental role in modern life. Petrochemical plastics, such as polyethylene (PE), polypropylene (PP), Polyvinyl chloride (PVC), Polystyrene (PS), and polyethylene terephthalate (PET), find extensive application in various fields, including electronics, packaging, construction, and aviation [1]. These synthetic plastic materials have high strength, light weight, resistance to corrosion, and low toxicity, also are inexpensive, easy to manipulate and easily formed into diverse products [2]. The major drawback of petroleum-derived plastics is their limited degradability, guiding to the persistence of plastic content in the environment for many years. More than 34 million tons of plastic wastes are generated each year throughout the world and 93% of them are disposed of in landfills and oceans [3]. Unfortunately, the global recycling rate is rather low, with only 9 % of used plastic. Although, the EU attempts to come up against the disposal of plastic wastes and improve reusing and recycling applications, developing countries are still dependent on the conventional landfilling. Incineration of plastic wastes were also primarily applied in European countries such as Denmark which had the highest rate of incineration (76%). Except for the generation a significant amount of CO_2, also, a huge amount of ash and slag who contain hazardous and toxic compounds which are required to be disposed, can cause other serious environmental problems [4].
Particularly, plastics used in everyday activities such as bags, packaging, and bottles undergo continuous degradation into smaller particles - microplastics (MPs <5 mm) or nanoplastics (NPs <100 nm), due to various external factors such as sunlight, pressure, wind, moisture, oxygen, heat, bacterial activity, and ionizing radiation. Microplastics are globally spread throughout the environment, and their negative impact is enhanced by their ability to adsorb organic pollutants and heavy metals [5]. Given these concerns, substitution of conventional plastics with sustainable material is necessary. In the last decades, bioplastics have garnered great interest in the research community.
The main objectives of this paper are to analyze the biodegradation of bioplastics and to investigate their ability to biodegrade under different conditions. In addition, this mini review is intended to highlight the potential of these materials, and their application in Republic of Serbia.

Bioplastics

Bioplastics were first manufactured in the 1950s and re-emerged in the 1980s, but in the 2000s received the necessary attention when their industrial-scale production began [6]**.** As an alternative to conventional petrochemical plastics, bioplastics have been proposed as an

environmentally friendly alternative. The main advantages of bioplastics are the fact that biogenic raw materials are used to manufactured them, needed less fossil fuel consumption, less toxic and sustainable, biodegradable, and environmentally friendly. Despite their many environmental advantages, bioplastics have disadvantages like higher prices and a lack of regulations [7].

Bioplastics are produced from edible feedstocks such as vegetable oil and starch as well as algae, wood, and agricultural wastes, e.g., sugarcane bagasse, corn stover, rice husk, and wheat straw [8]. The European Commission defined bioplastics as materials that are either a) produced from renewable resources; b) biodegradable; c) made through biological means; or d) a combination of the aforementioned requirements [9]. On the other hand, IUPAC provided recommended terminology for bioplastic, such as it could be a) bio-derived; b) industrially/home compostable; c) non-compostable or d) chemically equivalent to traditional plastics [10]. Most bioplastics are biobased and biodegradable (e.g., PLA, PHA); although there are biobased materials that are not biodegradable (e.g., bio-PET, bio-PE) [11]. In the Table 1 is given classification of the most produced bioplastic materials.

Bioplastics can be divided into three groups. The first group includes those that are bio-based and non-biodegradable (Bio-PE, Bio-PET, Bio-PVC, Bio-PU). In the second group is bioplastics that are bio-based and biodegradable (PHA, PHB, PLA) and the third groups, includes those that are synthesized by petrochemical feedstock but are still biodegradable (PBS, PCL, PBAT) [12]. The term bio-based means the product derived from biomass (plant materials). The group of mixed sources (bio/petro) includes biopolymers based on blends of Polyhydroxy alkanoates (PHA), Polylactic acid (PLA) produced by fermentation, biobased epoxy, biobased polyesters such as polytrimethylene terephthalate which are obtained from sugarcane biomethanol [13]. In fact, the production of bioplastics, as biopolimers, is mostly from agro-waste, plant residues, woodchips, starch, or microbes. The isolated monomers are converted to plastics thorough innovative fermentation or through polymer technology by using techniques such as casting, internal mixing, extrusion and injection molding.

Briefly, PLA is a biodegradable and bio-based polymer derived from renewable resources such as corn starch or sugarcane. It is the most commonly used bioplastics, with applications in various industries, such as packaging, textiles, 3D printing, biomedical implants, and disposable tableware. PHAs are a family of thermoplastic polyesters synthesized by microbial fermentation of renewable carbon sources like sugars or lipids. PBS is a biodegradable polyester produced from succinic acid and 1,4-butanediol, and had a similar property to PE and PP. PCL is a biodegradable polyester synthesized through the ring-opening polymerization of ε-caprolactone. Cellulose-based plastics are derived from the modification of cellulose.

Table 1. *Classification of the most produced bioplastics [14].*

	Source	Name	Abbreviation
Bioplastics	Petroleum based	Polybutylene succinate	PBS
		Polylcaprolactone	PCL
		Polyethylene succinate	PES
		Polybutyrate adipate terephthalate	PBAT
		Polyamide	PA
		Polyethylene	PE
		Poly(ethylene terephtalate)	PET
		Polypropylene	PP
	Bio-based	Poly(lactic acid)	PLA
		Polyhydroxyalkanoate	PHA
		Starch plastics	–
		Cellulose esters	–

		Bio-polyethylene	Bio-PE
		Bio-poly(ethylene terephtalate)	Bio-PET
		Bio-polyamide	Bio-PA

Approximately 2.47 million tons of bioplastic was produced in 2024 (Fig. 1), with degradable and non-degradable materials amounting for 1.55 and 0.86 million tons, respectively.

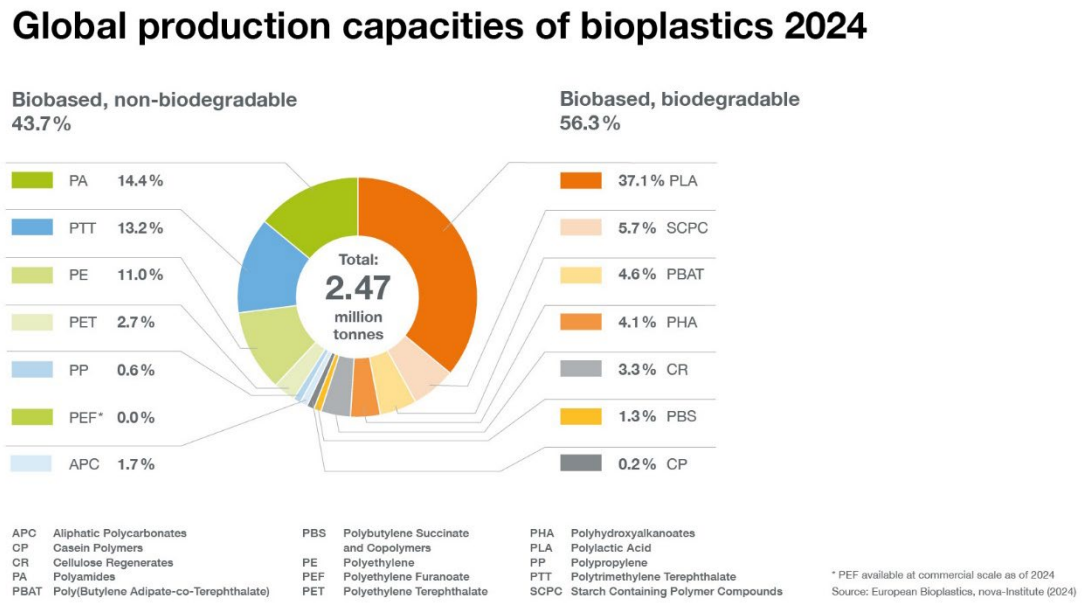


Fig. 1. *Global production of bioplastics 2024 (by material type) [14].*

The main advantage of these bioplastics is their capacity to biodegrade. The biodegradation of polymers consists of three important steps:
1. Biodeterioration, which is the modification of mechanical, chemical, and physical properties of the polymer due to the growth of microorganisms on or inside the surface of the polymers,
2. Biofragmentation, which is the conversion of polymers to monomers and oligomers by the action of microorganisms and
3. Assimilation where microorganisms are supplied by necessary nutrient sources, carbon, and energy from the fragmentation of polymers and convert carbon of plastic to CO_2, water and biomass.

Biodegradation can be further classified into aerobic and anaerobic according to the presence or absence of oxygen.

Aerobic biodegradation is the mineralization of organic compounds by the action of aerobic microorganisms in the presence of oxygen:
$$\text{Polymer} + O_2 \rightarrow CO_2 + H_2O + NO_2 + SO_2 + \text{biomass} + \text{heat} \quad (1)$$

Anaerobic biodegradation is the same process but in the absence of oxygen, resulting in the production of methane and carbon dioxide:
$$\text{Polymer} \rightarrow CO_2 + CH_4 + NH_3 + H_2O + H_2S + \text{biomass} + \text{heat} \quad (2)$$
In anaerobic degradation, energy is mainly released as methane, and less as a heat.

Polymer biodegradation is influenced by the combination of environmental factors (humidity, light, temperature, pH, nutrient supply, etc.) and the physio-chemical characteristics of the polymer (molecular weight, hydrophobicity, morphology, crystallinity, porosity, etc.). The biological degradation occurs by surface erosion, where extracellular enzymes operate only on the polymer surface, which prevents them from penetrating deeply into the polymer matrix. The process cross through three steps: first were microorganism interaction with the polymer surface, the second step is microorganisms' growth multiplying itself and breaking down the polymers and lowering their molecular weight. And finale step is mineralization of the polymer, where production of CO_2, H_2O, or CH_4 occurs. It should be noted, the process of biodegradation is influenced, excepting the material's physico-chemical structure, by the polymer's chain configuration. The longer the polymer's chain is, the more difficult it is to degrade. However, the polymer's crystallinity is also an important parameter of biodegradation, as the amorphous parts of the polymer are, easier to degrade, compared to the crystalline parts.

Biodegradable polymers are decomposed by microbial attack. More than 90 types of microorganisms are responsible for biodegradation in different environments. Besides microbes, bacteria and fungi are involved in bio-polymers' biodegradation. Various microorganisms isolated from soil environments utilized bioplastics as the carbon source. Actinobacteria species suchas *Amycolatopsis*, *Thermomactimyces*, *Actinomadura*, *Nonomuraea*, *Laceyella* and *Streptomyce*s species were obtained from soil among which *Amycolatopsis* and *Streptomyces* were the most common species. *Paenibacillus*, *Pseudomonas*, *Bacillus* and *Bulkholderia* species were mainly isolated from different soil environments and they were capable of degrading the bioplastics. Among the soil isolated fungi species responsible for bioplastics biodegradation, *Aspergillus*, *Fusarium* and *Penicillium* were the main species. In the Table 2 is given the microbes used in biodegradation different types of bioplastics.

Table 2. *Types of bioplastics and the microbes used in biodegradation [15].*

Type	**Microbes**	**Use**
PHB	*Rhizosphere, Alcaligenes eutrophus, Azotobacter beijierinckia, Pseudomonas oleovorans, Rhizobium sp*	Soil *Rhizosphere* of maize, wheat and trefoil eighteen PHB producers
Cellulose	*Pseudomonas strains, Neisseria sicca, Alcaligenes xylosoxidans*	Degrade cellulose acetate with DS1.8 And DS2.3. The highest degradation rates reported were 60 and 45% within 20 days.
Starch	*Pseudomonas aeruginosa*	Produces Polypropylene
protein base	*Bacillus subtilis* and *Escherichia coli*	Using cane molasses as an inexpensive substrate.
Polylactic acid	*Rhizopus delemar*	Pure lactic acid production, end product of fermentation
Polyurethane	*Pestalotiopsis microspora*	Ability to degrade the synthetic Polymer Polyester polyurethane (PUR), useful for bioremediation
Polydiethylene adipate	*Comamonas acidovorans, Pseudomonas aeruginosa, Pseudomonas stutzeri, Streptomyces badius*	Waste management, and their Consumption is increasing day by day at a rate of 12% per annum

Enzymes which can be either intracellular or extracellular, are responsible for enzymatic degradation of bioplastics. The optimal temperature range for enzyme activity is between 25°C and 40°C. Enzymatic degradation of polymers relies on the potential of microorganisms to produce specific enzymes such as depolymerases. These enzymes hydrolyze the polymers into water-soluble forms, so it can be dissolved in water for rapid biodegradation [16].

At the end of this short presentation on the types and ways of obtaining bioplastics, we will mention the advantages of biodegradation of bioplastics and environmental benefits. First of all is reduction in fossil fuel dependence, where plant starches, agricultural byproducts, and microbial fermentation are a few illustrations of the renewable materials used to make bioplastics. We expected lowered emissions of greenhouse gases, and at the same time cultivating plants to produce bioplastics can aid to achieve carbon neutrality by storing CO_2. The most important advantages of biodegradation of bioplastics is reduced accumulation of plastic wastes. This will lead to better end-of-life care management, by composting, anaerobic digestion, and recycling of bioplastics.

The state of bioplastics in Republic of Serbia

Although the consumption of plastic in Serbia is lower compared to the average of the European Union - about 100 kilograms per inhabitant per year, the growth trend is present. Estimates indicate that around 200,000 tons of plastic are disposed of annually in landfills in Serbia, where they remain for hundreds of years due to the slow decomposition process. However, global demand for plastic materials continues to rise despite environmental challenges, with increasing attention to recycling and the development of biodegradable plastics. In Serbia, there is currently no data on the amount of bioplastic that is produced, used and disposed of. Large quantities of (bio)plastics are also widely used for food contact, such as packaging or disposable tableware. According to the data of the Environmental Protection Agency [17], the amount of plastic placed on the market of the Republic of Serbia in 2024 is 194.3 tons. It is amount of conventional plastics. Also, general packaging waste management targets for 2023 are set at 65.8% for waste reuse and 62.5% for waste recycling.
There is no data on the use of bioplastics, so it can be concluded that they are not widely represented on the Serbian market, mainly through single-use packaging.

CONCLUSION

The production of bioplastics has received significant attention from the public in recent times, due to its contribution to the protection of the environment and the preservation of the ecosystem. The present study demonstrates the benefits of bioplastics as a potential alternative to single-use plastics and the concept of sustainable development, i.e. "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Moreover, the environmental impact caused by the large quantity of non-degradable waste materials is promoting research to develop new biodegradable materials that can be manufactured from natural resources like biomass, plants, bacteria. So, the new developments of bioplastics in the future can cause the efficiency of production will be increase, develop new applications and new opportunities of bioplastics. Nowadays, manufacture bioplastic could be significantly applying and commercialize for various industries such as agriculture, medical, pharmaceutical, veterinary, etc.
Bio-based plastics and biodegradable plastics can affect the environment and human health to different degrees, and this depends to a great extent on the type of material, the individual product and its specific life cycle. Therefore, bioplastic is not the solution for all the problems related to the current use of plastic. The application and further development of bioplastics require careful weighting and balancing between their limitations and benefits.

REFERENCES

[1] Islam, M., Xayachak, T., Haque, N., Lau, D., Bhuiyan, M., Pramanik, B. K., Impact of bioplastics on environment from its production to end-of-life. Process Safety and Environmental Protection 188 ,151–166, 2024.
[2] Geyer, R., Jambeck, J.R., Law, K.L., Production, use, and fate of all plastics ever made. Sci. Adv. 3, e1700782, 2017.https://doi.org/10.1126/sciadv.1700782.

[3] Emadian, S. M., Onay, T.T., Demirel, B., Biodegradation of bioplastics in natural environments. Waste Management 59, 526–536, 2017.
[4] European Commission, 2011. Plastic Waste in the Environment, Final Report. http://ec.europa.eu/environment/waste/studies/(20.09.2025)
[5] Wang, C., Zhao, J., & Xing, B., Environmental source, fate, and toxicity of microplastics. Journal of Hazardous Materials, 407, 124357. https:// doi. org/10. 1016/j. jhazm at. 2020. 124357, 2021.
[6] Song, J.H.; Murphy, R.J.; Narayan, R.; Davies, G.B.H., Biodegradable and compostable alternatives to conventional plastics. Philos. Trans. R. Soc. B Biol. Sci. 364, 2127–2139, 2009.
[7] Casarejos, F., Bastos, C.R., Rufin, C., Frota, M.N., Rethinking packaging production and consumption vis-` a-vis circular economy: a case study of compostable cassava starch-based material. J. Clean. Prod. 201, 1019–1028, 2018.https://doi.org/10.1016/j.jclepro.2018.08.114.
[8] Brockhaus, S., Petersen, M., Kersten, W., 2016. A crossroads for bioplastics: exploring product developers' challenges to move beyond petroleum-based plastics. J. Clean. Prod. 127, 84–95. https://doi.org/10.1016/j.jclepro.2016.04.003.
[9] Rosenboom, J.-G., Langer, R., Traverso, G., Bioplastics for a circular economy. Nat.nRev. Mater. 7 (2), 117–137, 2022.
[10] Vert, M., Doi, Y., Hellwich, K.-H., Hess, M., Hodge, P., Kubisa, P., Rinaudo, M., Schu´ e, F., Terminology for biorelated polymers and applications (IUPAC Recommendations 2012). Pure Appl. Chem. 84 (2), 377–410, 2012.
[11] Costa, A., Encarnaç ao, T., Tavares, R., Todo Bom, T., Mateus, A., Bioplastics: innovation for green transition. Polymers 15 (3), 517, 2023.
[12] Awasthi,S. K., Kumar, Kumar, M. V., Sarsaiya, S., Anerao, P., Ghosh, P., Singh, L., Liu, H., Zhang, Z., Awasthi M. K., A comprehensive review on recent advancements in biodegradation and sustainable management of biopolymers. Environmental Pollution 307, 119600, 2022.
[13] Sidek, I. S., Draman, S. F.S., Abdullah, S.R.S., Anuar, N., Current development on bioplastics and its future prospects: an introductory review. i TECH MAG Vol 1, 03-08, 2019.
[14] European bioplastic, 2025. https://www.european-bioplastics.org/bioplastics/materials/ and https://www.european-bioplastics.org/bioplastics/waste-management/
[15] Sharma, N.,Akhtar, S.,Khan M.K.A., Bioplastics advances and their role in the management of plastic pollution. Neuropharmac Journal 6, 229-240, 2021.
[16] Suzuki, M., Tachibana, Y., Kasuya, K.I., Biodegradability of poly (3- hydroxyalkanoate) and poly (ε-caprolactone) via biological carbon cycles in marine environments. Polym. J. 53 (1), 47–66, 2021.
[17] https://sepa.gov.rs/wp-content/uploads/2024/10/Ambalaza-2023.pdf 24.09.2025

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ENERGY CRISIS AND GLOBAL WARMING - THE NECESSITY OF A PARADIGM CHANGE

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Abstract: The paper points out the necessity of changing the climate paradigm; instead of mitigating global warming, we should work on planetary climate management. Therefore, the idea of a climate millennium intervention – as a model of climate management – is presented, which the author published in 2008 in his book "Three Essays on Science" and sent to the GOOGL public competition "Ideas that change the world". These proposals did not have a major impact on the professional and scientific public, but – as the existing practice of adapting to global warming has not proven successful in the past two decades – the need to initiate a planetary discussion on the proposed model of climate management is once again pointed out.
Key words: Air currents, Climate control, Global warming, Ocean currents, Orbital lampshade

1.INTRODUCTION

In 2008, at the GOOGLE competition Ideas to Change the World with Project 10^100 (September 24, 2008), I submitted the idea "Millennium Climate Intervention", which is also described in my book "Three Essays on Science" (fig. 1); [1]. Basically, it is a proposal to place an orbital lampshade in the Earth's geostationary orbit in order to reduce solar radiation by a certain percentage and thus begin to manage the Earth's climate (Fig. 2). This would provide the necessary time for the use of climate-neutral energy sources. For that occasion - according to my template, a younger colleague from the Faculty - then assistant Zoran Balkić - made a 30-second video simulation of the said idea (fig. 3).

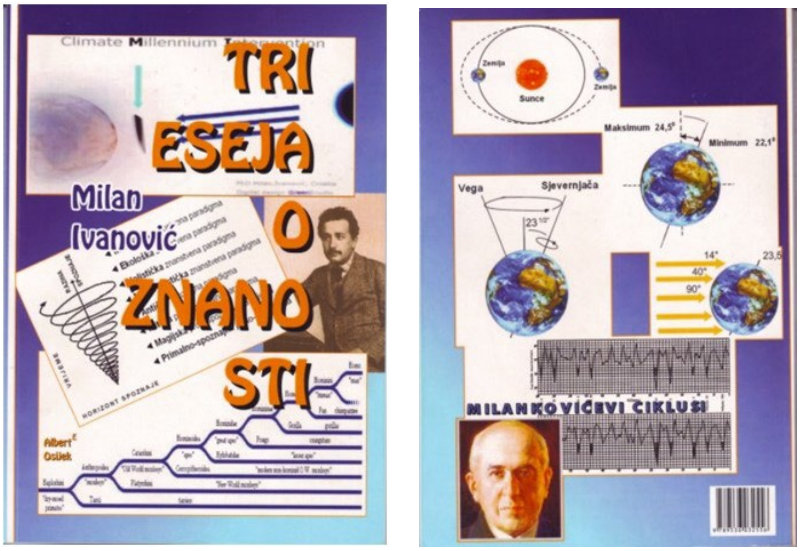


***Fig. 1**: Cover of the book "Three Essays on Science" and the back cover of the book showing Milanković's climate cycles* [1]

Over 150,000 works were submitted to the aforementioned GOOGLE competition, and my proposal for the "Millennium Climate Intervention" was not selected for the award - because according to the propositions, the idea had to be commercial and feasible within two years. I also presented the idea of the "Millennium Climate Intervention" at the international conference VIPSI-2009 Belgrade (Fig. 4).

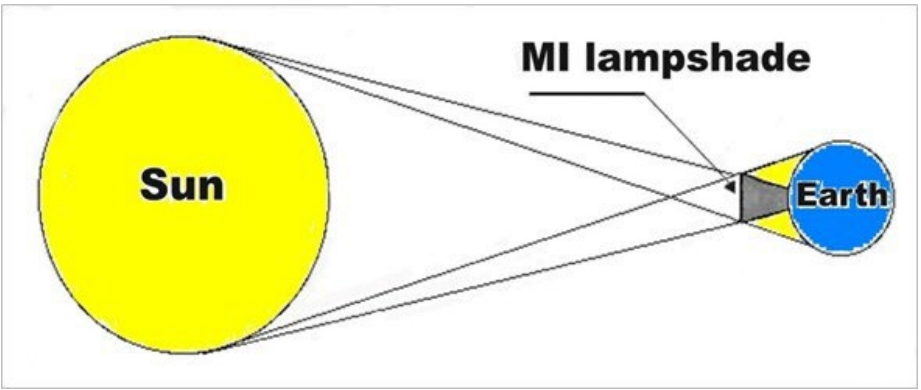


Fig. 2. *Schematic representation of the Millennium Climate Intervention* [1]

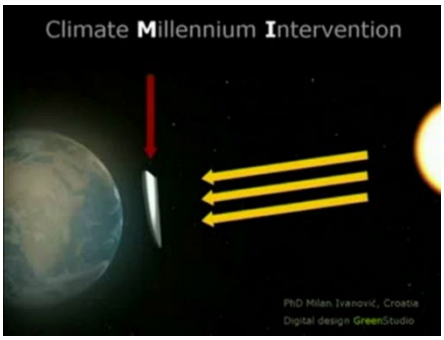


Fig. 3*: The first sequence of the 30-second video "Millennium Climate Intervention" (2008)* [1]



Fig. 4*: Power point presentation cover on VIPSI Belgrade conference (2009)* [2] [3]

2. FROM THE KARDASHIAN SCALE TO THE MILLENNIUM INTERVENTION

I worked on the book "Three Essays on Science" (along with obligations at the Faculty and the publication of a dozen books and over 400 papers) for almost 20 years; In the chapter "Laws of the World and the Scientific Paradigm" to illustrate the laws of scientific knowledge, I carefully searched and studied the literature with which I would clarify the differences between the laws that govern: (a) the inorganic world (the law of gravity, for example), (b) the laws in nature (the law of inheritance, for example), and (c) the laws that manifest in society (the law of supply and demand in economics, for example). In this way, for the first group of laws, I processed Kepler's laws, Hubble's law, and the Milanković cycles. Thus, while studying the literature, I became acquainted with the **Nikolai Kardashev scale** and the papers by **Carl Sagan** and **Freeman Dyson** about the level that human civilization has achieved on the path to Type I civilization.

The Kardashev scale (K-scale) has become a general method of classifying the technological progress of civilizations; has three categories, based on the amount of energy used by hypothetical civilizations. [4] [5]

Type I. - A civilization capable of using the available energy of its planet
Type II. - A civilization capable of using the available energy of its star
Type III. - A civilization capable of using the available energy of its galaxy

It should be emphasized that this is about hypothetical (extraterrestrial) civilizations. In addition to theoretical considerations in the development of civilization, which this model of energy use gives a framework for, the Kardash scale is also used in SETI research (Search for Extraterrestrial Intelligence). Human civilization is still below Type I civilization, and the current status of human civilization - according to the Kardash scale - is called Type 0. Although the stage values were not discussed in Kardash's original proposal - the American astronomer Carl Sagan (1934–1996) calculated (using the Kardash formula and energy consumption data) that human civilization (in 1973) had reached level 0.69 [6], and the American physicist Freeman Dyson (1923–2020) made an estimate of the transition of human civilization to Type

I according to which our civilization reached level 0.72 in 2004, and in 2030 it will be at level 0.73. [6],
American physicist Michio Kaku emphasizes that there is a significant set of problems that humanity must overcome in time for human civilization to reach a higher status, i.e. reach the level of Type I civilization. He emphasizes that a civilization that has not reached Type I may be subject to crises, dangers and catastrophes; today, planetary political and social development lags behind technological development and is threatened by ecological collapse (which requires planetary policy to solve such problems), as well as threats of an ice age, collisions with meteors, etc. Kaku cites Dyson's calculation for the achievement of Type I civilization - around the year 2200. This estimate is based on a linear extrapolation of current technological achievements in energy use on Earth - at a rate of 1% per year, and Kaku himself believes that this could happen as early as the 21st century. [7], [8]. Due to the acceleration of the emergence of new scientific knowledge - we believe that Kaku's estimate is justified.
Climate management on the planet is also a fundamental issue for Type I civilizations; this type of civilization, according to Kaku, manages the climate of its planet because it controls the planet's available energy potential. However, Kaku did not answer how to achieve this on our planet, although he points to the need to research technologies that will efficiently extract useful forms of energy from the vast energy potential in the oceans (solar radiation). [9]

2.1. Energy crisis and global warming - the necessity of a paradigm shift

The energy crisis (due to the large increase in energy consumption, and limited resources on Earth) which manifests itself in increasingly expensive energy production and increasing environmental damage - requires new perspectives on the entire energy sector. In addition to this very significant technological and economic problem, today's civilization is faced with another - increasingly serious challenge - global warming, which threatens not only economic troubles but also an ecological danger for civilization in today's context. The climate changes over time under the influence of its own (internal) dynamics and due to external influences. External influences include natural phenomena (e.g. volcanic eruptions or solar variations - Milanković cycles), as well as human activity, which leads to changes in the composition of the atmosphere. Every second, the Earth's atmosphere receives 1.37 W of solar energy per 1 m2 of surface area (which is exposed to the Sun). About 30% of this radiation is reflected into space; about two-thirds of this reflection arises from clouds and particles in the atmosphere (aerosol), and surfaces under snow, ice and deserts reflect the remaining third.
Research on global warming by 2000 has shown the seriousness of the situation; data confirms that the earth's climate is changing rapidly. The IPCC (Intergovernmental Panel on Climate Change) has confirmed that global warming is indisputably proven. Unfortunately, efforts to mitigate the warming process so far have been insufficient; many countries have not achieved the goals of the 1997 Kyoto Protocol (which entered into force in 2005 as an addition to the international climate change agreement, signed with the aim of reducing emissions of carbon dioxide and other greenhouse gases). The situation is similar with the implementation of the Paris Agreement (from 2015), according to which countries should work to keep global warming below 2 degrees - in order to avoid the worst effects of climate change. However, practice is recording increasingly serious consequences of climate change. The year 2024 was recorded as the warmest in history, surpassing the previous record from 2023, and extreme weather events, such as devastating fires or urban floods, are becoming more frequent. Global temperature has increased by 1.324 C0 in the last 100 years. (Fig. 5 - 6)
The World Meteorological Organization (WMO) has confirmed that 2024 was the warmest year on record, based on six international datasets. The past ten years have been among the ten warmest, with 2024 being about 1.55 °C above pre-industrial levels. [12]
The scale/dynamics of global warming are best shown by satellite images of the North Pole (at the same time of year) and Grenland (Fig. 7 - 9)

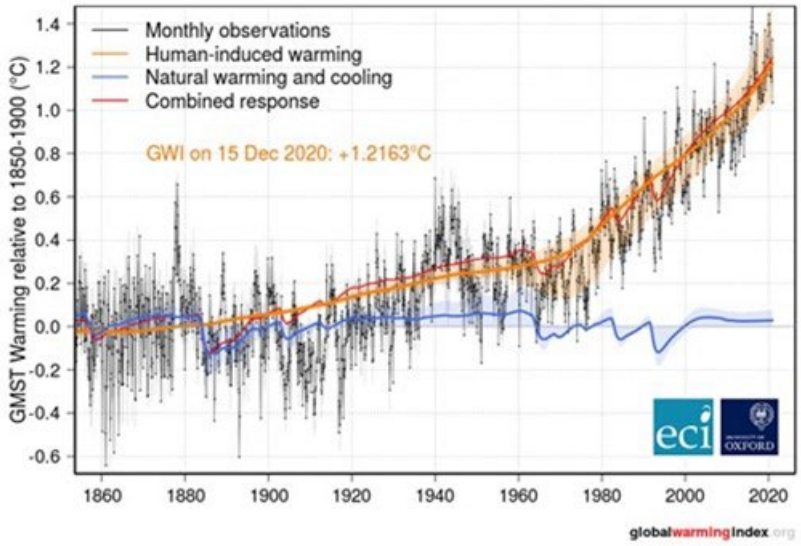


Fig. 5. *Global Warming Index (aggregate observation) on Earth updated to Dec. 2020* [10]

Legend
- The black line shows the actual observations of global mean temperature. Although there is some annual variation, the Earth's temperature has been rising steadily since the 1960s. This cannot be explained by natural causes. The blue line shows the estimated contribution to the change in Earth's temperature from natural causes, such as changes in solar activity and volcanic eruptions. These explain some of the variation in global temperatures, but they cannot explain the total warming.
- The orange line shows the estimated contribution of human-induced global warming, caused by burning fossil fuels or other forms of pollution. Because this line closely follows the temperatures observed in the real world, it shows that the overall warming can largely be attributed to human activity. However, it is still not an exact match.
- The red line shows the combined effects of human-induced and natural changes. This line best matches the observed temperatures and shows that human-induced changes, plus some natural influences, have caused the global warming we see today.

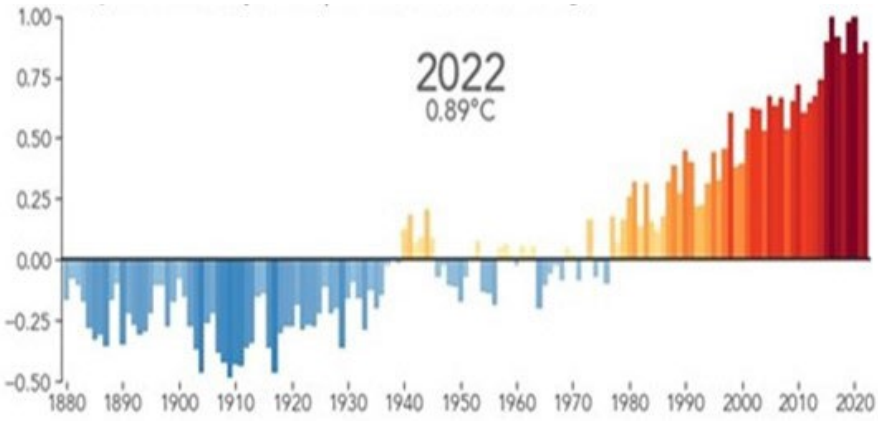


Fig. 6. *Global Temperature Anomaly (^{0}C compared to the 1951.-1980 average)*
Last 9 years Warmest on Record [11]

According to current measurements - average temperatures on Earth could increase by several degrees C by the end of the century with far-reaching effects; sea levels will rise and flood coastal areas, there will be severe droughts and large fires will occur more often, insect-borne diseases will spread significantly, and many animal and plant species will be at risk of extinction. According to earlier estimates - an increase in average temperatures by 1.5°C to 2.5°C between 20 and 30% of higher plants and animals will be at risk of extinction. According to other estimates - if the global temperature rises to 4.6°C (compared to the pre-industrial period), the Greenland ice sheet will be threatened, the melting of which will raise sea levels by as much as 7 m.

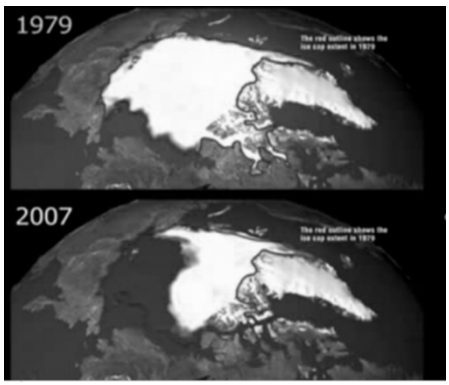


Fig. 7. Melting of the ice cover at the North Pole from 1979 and 2007 [13]



Fig. 8. Melting of the ice cover at the North Pole from 2025 [14]



Fig. 9. *The Greenland Ice Sheet is shrinking for the 29th year in a row* [15]

With the disappearance of the snow cover in the northern regions (Greenland, Siberia, Alaska), two new unfavorable processes have begun:
- deposited methane is released from the thawed soil; large methane emissions into the atmosphere will increase and accelerate the greenhouse effect on our planet.
- the areas under snow on the planet that reflect solar radiation have been significantly reduced - which contributes to greater heat retention on the planet. [16]

2.2. How to solve this issue of the survival of human civilization?

It is certain that the efforts made so far to understand these changes are valuable - but it should be emphasized that serious warnings about climate change were given even 50 years ago, and the politics and economics of this civilization, unfortunately, were not up to the level of the problem. The UN Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol, the International Panel on Climate Change (IPCC), the Paris Agreement, the initiatives of the EU and other supranational and national institutions are on the right track, but they are coming with a significant delay; the implementation of these measures is a particularly problematic issue. In addition, in our opinion, all models of solutions to global warming move within the framework of the existing scientific (ecological) paradigm - which is dysfunctional in a number of elements.
Solutions that propose reducing greenhouse gas emissions and other measures to mitigate global warming are certainly welcome, but the cycle of normalization of CO2 and other greenhouse gases in the atmosphere is much longer than the available time left according to

warning scenarios. This means that these measures will not prevent global warming from increasing to a level that will not threaten the existing climate regime and the ecological framework of the current state of the planet – even if all countries in the world accept emission reductions (!) and all of them adhere to the planned reduction rates (!).

3. A QUANTUM LEAP INTO A TYPE I. CIVILIZATION

We believe that the existing scientific paradigm and the existing scientific research programs do not offer satisfactory solutions for the coming (big) climate changes in the time frame that remains before the devastating climate consequences. Here we should also express our surprise that in the formulation of existing climate models of global warming, solar radiation is taken as a constant (with the addition of different values for anthropogenic and planetary natural variables). Such an approach certainly makes it difficult to solve the equation of climate change and current efforts to reduce global warming. Likewise - we believe - that the previous forecasts (Dyson and others) of reaching the status of Type I civilization (which start from the linear extrapolation of past energy consumption and extraction technology) are not correct, because - in physics (and science), as well as in technology, there has never been a linear development - so Dyson's method (extrapolation of a linear trend with an increase of 1% per year) basically represents an extrapolation of the past into the future. We must reckon with a quantum leap - as the logic of science implies and as the history of scientific discovery shows.

Our approach to the solution starts from a paradigm shift and creating the conditions for a quantum leap into a Type I civilization - one that controls the available energy and manages the climate of its planet.

3.1. How to manage the climate on Earth?

On the Internet forum of the American physicist Michio Kaku, one participant (2 years ago) asked the question – "how, in general, can the climate on Earth be managed (?)" – and concluded that it is impossible; no one on the Forum answered. We, on the other hand, believe that today's civilization can manage the climate on Earth – only, for this to happen, it is necessary: a) a change in the scientific paradigm, b) the establishment and development of a new planetary scientific program (with a special emphasis on the development of solar technology and new climate models), and c) planetary government.
In the time of previous scientific paradigms (mechanistic and holistic), science did not consider ecological issues (in today's framework); even more so – the development of civilization (within the framework of such scientific worldviews) disrupted the natural balance, endangered a number of ecological conditions on the planet and significantly contributed to the greenhouse effect that contributes to global warming processes. Proponents of the ecological paradigm, on the other hand, emphasize: nature should not be managed but should be cooperated with; This paradigm advocates sustainable development and reduction of environmental pollution and human life in partnership with nature. In this (proposed) partnership, non-aggressiveness of man towards nature is essential and it is necessary to develop new so-called clean technologies and use clean energy; this is especially after the observed processes of rapid climate change (global warming). However, the time horizon available - with the existing level of economic and technological development on the planet - is not sufficient to implement the techno-economic changes of the ecological paradigm in time.
In the current conditions (ex post ecological framework set) and the available time horizon, this kind of orientation in some way - we believe - aims to preserve the development of civilization, that is, it can hinder the ambitions of further development and be a big obstacle to the direction/reach of the level of Type I civilization. Such an attitude in a certain way (implicitly) leads to the regression of human nature - which we consider disastrous. We believe that it is necessary to continue to develop civilization through the proactive action of man on the conditions of his life with the mentorship of nature, i.e. we advocate the Millennium Intervention, which should enable the development of civilization on a new basis while maintaining the present planetary eco-system.

The logic of science grows and develops spirally - starting from scientific facts, through scientific laws and scientific theories to a scientific paradigm. In the further development of science (in the model of accelerated growth of knowledge), in addition to the scientific paradigm (as the supreme principle of science), there must necessarily exist a civilizational (planetary) research program in the meaning of the settings of Imra Lakatos. And finally - the existing approach does not indicate models of proactive climate management - and it is (on the one hand) a priority technological, energy and eco-logical issue of civilization and (on the other hand) it is the management of ecological conditions (climate) one of the essential features of advan-ced civilizations.

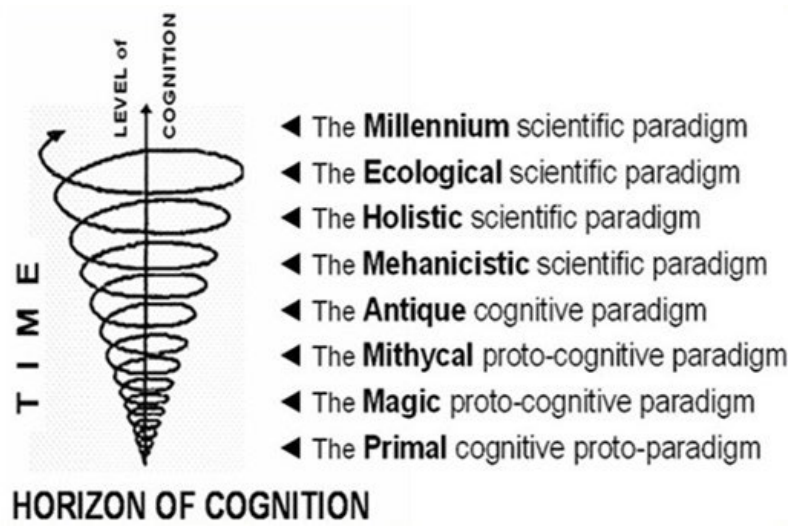


Fig. 10. *The logic of growth of scientific paradigms* [1]

3.2. Millennium climate intervention

The quantum leap is based on our heuristic model of the solar program, which is based on the Millennium Intervention (MI), i.e. the placement of an orbital lampshade that acts as an obstacle to solar radiation with its surface, reducing the insolation of the Earth; Possible creation of: (a) a mechanical type screen (a kind of aluminum foil) or (b) other so-called 'cloud variants' - such as floating leaflets in an electromagnetic field, or some kind of smoke curtains. By applying MI lampshades, a permanent shadow would be created at a certain place on the planet: a) on warm sea currents that threaten arctic areas, or b) where glaciers are melting or c) around 65^0 north latitude (Milanković). In this way, solar radiation on the Earth should be reduced, according to the calculation and the degree of progress of greenhouse gases and/or other anthropogenic, natural or cosmic causes of global warming. Of course, it is necessary to first research and create new climate models that will calculate: - the optimal allocation of the MI shadow, - the effects on changes in the direction and intensity of (new) air movements (wind), - the effects on changes in the direction and intensity of (new) sea currents and - the change in temperature (MI shadow) of the surrounding areas. Therefore, solar technology should rise above the Earth's surface and, in orbital conditions, enable climate management and the acquisition (and transport) of energy to the Earth. Scientific research and development of technology within the framework of the solar program are unthinkable without values adopted by consensus, i.e. for such technological ventures and for the realization of the MI screen project, the partnership of all countries on the planet and the planetary government is required, because the issue of the location of the MI screen shadow will be an issue of changes in eco-conditions, on which there will have to be an intercontinental consensus and the authority of the planetary governments.

4. CONCLUSION

- Insufficiently effective measures against global warming - within the existing ecological scientific paradigm - should be replaced by a new approach based on a new scientific (millennium) paradigm.
- Instead of trying to mitigate global warming, a new millennium scientific paradigm should be used to manage the planet's climate.
- The new scientific Millennium Paradigm and the Millennium Climate Intervention can be the first real steps towards a Type I civilization.
- It is high time to start a planetary discussion on this.

REFERENCES

[1] Ivanović, Milan, Tri eseja o znanosti (Three Essays on Science), ISBN 978-953-6032-56-6, Elektrotehnički fakultet Osijek, 2008
[2] https://vipsi.org/ipsi/conferences/importantbefore.php?id_imp=122
[3] https://www.slideserve.com/xylia/ph-d-milan-ivanovi-university-of-osijek-faculty-of-electrical-engineering-osijek-croatia
[4] Kardashev, N. (1964.) Transmission of Information by Extraterrestrial Civilizations, Soviet Astronomy, 8, 217
[5] Kardashev, N. (1984.) The Search for Extraterrestrial Life: Recent Developments, Proceedings of the Symposium, Boston, MA, June
[6] Sagan C. (1973) Cosmic Connection: An Extraterrestrial Perspective, in J. Agel: F. Dyson, D. Morrison (2000), Cambridge Press (ISBN 05-21-7830-38)
[7] Kaku, M. (1999.) Visions: How science will revolutionize the 21st century Amazon
[8] Kaku, M. (2004.) The Physics of Extra-Terrestrial Civilizations, Astrobiology Magazine, April
[9] Kaku, M. (2006.) The Physics of Interstellar Travel, Cosmos, February https://mkaku.org/home/articles/the-physics-of-interstellar-travel/
[10] https://www.globalwarmingindex.org/
[11] https://earthobservatory.nasa.gov/world-of-change/global-temperatures
[12] 2024 as warmest year on record at about 1.55°C above pre-industrial level https://wmo.int/news/media-centre/wmo-confirms-2024-warmest-year-record-about-155degc-above-pre-industrial-level
[13] www.nasa.gov (access 8.8.2008)
[14] https://storymaps.arcgis.com/stories/8786a5f3cdda4ae1864de56332d59a94
[15] https://eng.geus.dk/about/news/news-archive/2025/september/greenland-ice-sheet-massbalance-2025 (access 28.8.2025)
[16] Demetrios Karis, Civilization will Collapse (High Confidence) :A Compendium of Relevant Biophysical, Political, Economic, Military, Health and Psychological Information on Climate Change, preprint, Bentley University https://ui.adsabs.harvard.edu/abs/2024EaArX...X5G404K/abstract
[17] Ivanović, Milan, Milenijska klimatska intervencija, 23. skup o prirodnom plinu i toplini, Osijek (Croatia) September, 24.-26.2025. Zbornik radova, pp 108-117
[18] Ivanović Milan, Scientific Paradigm and Electrical Engineering, 13th Scientific Conference Research and New Technologies, Faculty of Engineering and Information Technology. Pecs (Hungary) 1998.
[19] Ivanović, Milan, New Technologies and Scientific Paradigm, 20th conference. Research and New Technologies, Subotica, 2004. Polytechnic Engineering College Subotica (Serbia), Proceedings, pp 123 – 132
[20] Ivanović, Milan, Milutin Milanković (1879 –1958) – One of the Most Significant Scientists of 20th Century, 1st International scientific conference „Economy of Easter Croatia ", Osijek, May 20, 2012; ISBN 978-953-253-106-0, Proceedings, pp 326-335
[21] Ivanović, Milan, Milutin Milanković (1879 – 1958) kao građevinski inženjer, 11. simpozij Povijest i filozofija tehnike, ISSN 2939-0710, CIGRE, Zagreb, 2023. Proceedings, pp 435-458

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EVALUATION OF SETTLEABLE PARTICULATE MATTER IN TIMISOARA AND ZRENJANIN. FIRST STEPS AND PERSPECTIVES

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Abstract: This work presents the first steps taken in assessing the SPM – Settleable Particulate Matter pollution in cities of Timisoara (Romania) and Zrenjanin (Serbia). The study began by deploying identical non-directional deposition gauges (samplers) in 7 locations in Timisoara and 3 locations in Zrenjanin. The samples were collected monthly and analyzed in laboratory in full compliance with ASTM D1739 international standard. In this step only concentrations of SPM were determined, in the next steps of the study the assessment of heavy metals content of settleable atmospheric dust will be conducted.
Key words: SPM, Air Quality, Settleable Particulate Matter, Gravimetric Method

INTRODUCTION

The atmosphere contains much more than just "air". Besides gases, the lower atmospheric layers contain large amounts of particulate matter (or aerosols) with different diameters and shapes. A particle is frequently and mistakenly referred to as an aerosol. However, the term aerosol describes a mixture of gas, typically air, and fine solid or liquid particles that are suspended within it. Particulate matter is just one of the components of an aerosol. For these particles to stay suspended in the gas, their rate of descent must be low. It is generally understood that the spherical particles in an aerosol have a diameter of less than 100 μm. Aerosols span a wide range, from just a few tens of nanometers (smaller than a virus) to several tens of micrometers, comparable to the thickness of human hair. Their size and chemical makeup determine how far they can travel through the atmosphere, how they interact with solar and thermal radiation, and what impacts they may have on human health. When released directly into the air, they are called primary aerosols, such as sea spray, mineral dust, smoke, and volcanic ash. In contrast, secondary aerosols form in the atmosphere when gases or other substances undergo chemical reactions, as seen with sulfate aerosols produced from volcanic activity or industrial pollution. Over time, all aerosols can continue to change through additional chemical transformations, a process known as aging. [1]
The particulate matters (aerosols) are emitted from two major group sources, natural and anthropogenic and their lifetimes range from hours to years, depending on the size of the particles and the height at which they are injected into the atmosphere. The main global sources are the natural ones, from sea spray aerosols, mineral dust (from deserts and degraded soils), biomass burning and volcanic eruptions to biogenic aerosols. For example, the Saharan dust injected into atmosphere is estimated between $400 \cdot 10^6$ and $700 \cdot 10^6$ tons per year and is transported globally affecting air quality. [2] The second group is represented by anthropogenic generated (of affected by industrial/agricultural pollution) aerosols, mainly from energy sector, cement industry, industrial processes and agriculture. The latest methodology distinguishes 392 source categories for particulate matter. [3]
Particulate matter is classified in three size classes, fine fraction (PM2.5) abbreviated PM2.5, coarse fraction (PM10) and settleable (or suspended) fraction (SPM or TSP). The corresponding aerodynamic particle diameters are ≤ 2.5 μm, ≤ 10 μm and ≤ 100 μm. If the PM2.5 and PM10 fraction are of direct interest for impact on human health due to direct alveoli or thoracic aspiration, the SPM fraction is more or less an indication on annoyance levels.

Numerous studies showed that low particles deposition levels of 5 [g/m^2·30 days] is perceptible and cause health and annoyance issues. [4]

MATERIAL AND METHODS

Settleable Particulate Matter (SPM) is of particular concern because it can deposit onto surfaces, accumulate in the environment, and contribute to long-term impacts on air quality and human health. SPM consists of relatively large particles that settle primarily by gravity and can serve as carriers of environmental contaminants, especially metals released from industrial, mining, and urban activities. For instance, metals such as Pb, Cd, Ni, and Cr have been detected in SPM collected from both urban and industrial sites, raising serious environmental and public health issues. Similarly, research conducted in a mining and smelting region of southwestern China found elevated concentrations of Cd, Cr, Cu, Pb, and Zn in settleable particles, with values surpassing the limits set by the World Health Organization (WHO). [5]
The study area corresponds to two urban areas in Banat region, in the cities of Timisoara (Romania) and Zrenjanin (Serbia). Ten sampling points were established, covering industrialized, high traffic and urban/rural background types of land use, as shown in figures 1 and 2.



Fig. 1. *Location of SPM monitoring points in Timisoara*

For the location of sampling points different potential sources were considered and recorded: road traffic, railway and tramline traffic, industry, agriculture and commerce. One location was established in Timisoara as urban background (S3) in a low traffic, green area and a second one in Cornesti village (S2) as rural background.
The SPM passive, non-directional samplers were constructed at University Politehnica laboratory, in full compliance with ASTM-D1739-98(R17) reference standard: Standard Test Method for Collection and Measurement of Dustfall (Settleable Particulate Matter). The sampling vessel was made from glass and the holder from steel with aluminum wind screen deflector surrounding the vessel. All samples stand have a height of about 1.7 m. The sampling vessel diameter is 0.16 m, with a SPM collection area of 0.02 m^2.



Fig. 2. *Location of SPM monitoring points in Zrenjanin*

All samplers were exposed for 30 days (one month) and SPM samples were collected on site by washing the glass vessels with type II distilled water. In laboratory, the samples were first passed through a 1 mm mesh stainless steel sieve for impurities/insects' removal. The samples were then filtered through a fast filtering 47 mm No.10 glass fiber filters with a retention rate of 99.97 % in a Buchner funnel, separating the soluble to insoluble fractions of SPM. Both fractions were dried at 105 °C in a drying oven and desiccator. The weight of SPM was carried out by a 0.01 mg precision analytical balance.
In figure 3 an example of sampler placed on a sampling site is given.



Fig. 3. *SPM sampler in Timisoara, at INCUBOXX site with industry, rail & road traffic sources.*

RESULTS AND DISCUSSION

The calculation of SPM deposition rate was done following ASTM-D1739-98(R17) rules:

$$C_{SPM} = \frac{m_{SPM}}{A} \cdot \frac{30}{n} \quad [\frac{g}{m^2} \cdot month] \tag{1}$$

In equation 1, C_{SPM} and m_{SPM} represent the concentration respectively the mass of Settleable Particulate Matter; A is the area of the vessel in m^2; n is the number of days of exposure and 30 is a factor for normalizing the results to a month time.

The results obtained for a period of three months are presented in table 1.

Table 1. *SPM concentrations, in [g/m^2·month]*

	Timisoara							Zrenjanin		
2025	S1	S2	S3	S4	S5	S6	S7	ID1	ID2	ID3
April	16.6975	0.8175	5.9205	17.82	6.6865	6.523	3.24	3.399	1.7	2.206
May	15.8852	1.0927	5.2138	9.5245	6.1183	6.2807	3.108	2.104	1.795	1.054
June	16.4918	1.94	6.0324	5.978	4.2831	5.688	3.5157	2.508	1.68	2.642

As expected, the SPM concentrations were significantly higher in Timisoara sites than in Zrenjanin, as the city is more developed, with more industry and much more. In Romania, the limit for SPM in ambient air is 17 [g/m^2·month] but is applicable only for mining activities. Recorded SPM concentration at S1 (Brediceanu 23) is extremely high, but from all sampling points one should observe that for S1, located in the central Timisoara, all sources (except direct industry) are present: commercial, road, rail and tram traffic.

CONCLUSION

Even if PM2.5 and PM10 fractions are important to assess anthropogenic impact on public health, this study shows that SPM fraction is also relevant for large and dense urban agglomerations, for both annoyance and health consequences. However, the concentration is not of major interest for our future study, but the analysis of the SPM chemical composition. Thru this "first steps" we showed that SPM concentration in Timisoara and Zrenjanin are significant, the following steps would be to analyze the collected particles through graphite oven atomic spectrometry for targeted trace elements of heavy metal pollution: Pb, Hg, As, Al, Cd, Zn, as we expect them to be prevalent due to constant vehicular traffic and industrial zones.

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REFERENCES

[1] ***, NASA, Aerosols and Their Importance, Goddard Earth Sciences Division Projects, accessed on 24.09.2025, https://earth.gsfc.nasa.gov/climate/data/deep-blue/aerosols
[2] Loskot, J., Jezbera, D., Nalezinková, M. et al. Impact of Saharan dust on particulate matter characteristics in an urban and a natural locality in Central Europe. Sci Rep 14, 32002, 2024. https://doi.org/10.1038/s41598-024-83603-0
[3] Klimont, Z., Cofala, J., Bertok, I., Amann, M., Heyes, C., Gyarfas, F., Modelling Particulate Emissions in Europe, A Framework to Estimate Reduction Potential and Control Costs, International Institute for Applied Systems Analysis, Interim Report IR-02-076, 2014.
[4] Machadoa, M., Santosa, J.M., Reisenb, V.A., Reis Jr. N.C., Mavroidisc, I., Lima, A.T., A new methodology to derive settleable particulate matter guidelines to assist policy makers on reducing public nuisance, Atmospheric Environment, Vol. 182, pp. 242-251, 2018.
[5] del Pozo, D., Valle, B., Maza, D., Benítez, Á., Metal Enrichment in Settleable Particulate Matter Associated with Air Pollution in the Andean City of Ecuador, Environments, vol. 12, p. 304, 2025

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THE APPLICATION OF ENGINEERED PEACH STONE BIOCHAR IN REMOVING PHOSPHATES FROM AQUEOUS SOLUTION: KINETIC INSIGHTS

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Abstract (10 pt): New biochar-based material was synthesized via two-step process: pre-pyrolysis modification of waste biomass (derived from waste peach stones (PS)) and pyrolysis of chemically modified biomass. Obtained Mg-biochar composite (PS-M-B) was used for phosphates removal from aqueous solution in isothermal batch experiments under specified operational parameters. Sorption experiments were performed for the purpose of investigation of initial sorbate concentration (50-200 mg/l) and contact time (5 min to 24 h) on sorbent efficiency. It was observed that removal efficiency was higher than 90% after only 3 h of sorbet/sorbate contact and that equilibrium was achieved (in the whole concentration range) after 6 h of sorption. The overall rate of phosphate sorption from aqueous solution onto PS-M-B have been evaluated by non-linear form of two kinetic reaction models: pseudo-first and pseudo-second-order model. Obtained data followed better the pseudo-first order kinetics, indicating phisisorption as on of the most contributing mechanism in phosphate sorption process.
Key words: *waste biomass, chemical activation, biochar, phosphate removal, kinetics*

INTRODUCTION

Biochar (BC) is a solid, carbon rich multifunctional material produced by thermochemical conversion of mostly waste biomass in an oxygen-limited environment [1]. Huge amounts of feedstock are permanently available for BC production, among which agro-industrial residues are ones of the most importance due to the huge quantities generated all over the world and especially in developing countries [2]. As a low-cost material, BC has gained attention as an important material that can be applied in a diversity ways: as fertilizer that improves soil structure and promotes nutrient enrichment, as contaminated water/gas purifier, material for bioenergy production, additive to polymeric and concrete materials, super capacitor etc. [3,4]. Its valuable and sustainable role in variety materials production, promotes BC utilization in circular economy and suggest BC application as positive strategy for long-term decarbonisation [3,5].
The porous structure and active surface of biochar (full with functional groups) contribute to BC ability to bind variety pollutants from its environment [6]. However, unmodified, so-called "pristine" biochar has some limitations owing to its properties (e.g negatively charged surface, low specific surface area, and lack of specific functional groups, which may limit its utilization in sorption of specific pollutants (such as PO_4^{3-}) [7]. In order to improve that, the engineered biochars can be better alternatives instead of native biochars, because they have tailored sorbate binding capability and capability to slowly release bonded sorbates when applied into different matrix, for example into the soil. Physico-chemical modification might change the BCs morphology and surface area, change or induce new functional groups, metal contents, hydrophobicity etc. in such way to enhance the adsorption capacity and selectivity of BC towards specific pollutants [8]. Many studies have shown that these Metal-biochar-based composites can effectively enhance the adsorption capacity towards anions, especially phosphates. The modification method is usually carried out through impregnation and pre-pyrolysis or post-pyrolysis of the starting biomass [9].
A vast amount of waste biomass, which is generated in Serbia each year, can provide an excellent feedstock for BC production [2]. In order to examine potential of waste biomass

(generated from fruit processing industries) to bind one of the most abundant eutrophication agent-phosphate ions, the authors of this paper have modified it my Mg salt; the modified biomass was further tailored via pyrolysis under specific operational parameters and applied it in order to bind phosphate ions from synthetic solutions. Studies of the sorption kinetics provide insights into the overall rate of the sorption process, which is a crucial factor in evaluating the efficiency of the adsorbent, as well as giving insights into the sorption mechanism [9]. For that purpose, we have further examined the kinetic of this sorption process in order to get insight on possible kinetic mechanism.

MATERIAL AND METHODS

Waste biomass, peach stones (PS) was taken from the local fruit processing company "Fruvita", where they were characterized as a waste by-product. After receiving, stones samples were dried at room temperature and modified by Mg-salt according to the procedure adopted from Li et al. [10]. Modified PS samples were further pyrolysed into the biochar in pyrolytic reactor „APŽ-L-120-N; 03204" (Elektron, Serbia), at heating rate of 10 °C/min, from room temperature until 500 °C, where they were kept for 90 min. At the end of cooling process, biochar sample (PS-M-B) was grinded at desired granulation (d_p < 0.1 mm) and stored for further experiments.
Sorption experiments were performed in isothermal batch system with stirring, under previously determined sorption parameters: solid/liquid ratio=4 g/L, pH_i=5.5, T=25 °C, 200 rpm, while the initial phosphate concentration varied from 50 to 200 mg/L. The concentrations of residual phosphates were determined using MD 610 (Lovibond, Germany) at desired time intervals, which ranged from 5 minutes up to 24 hours.
The effectiveness (R(%)) and the sorption capacity (q_e) of the PO_4^{3-} sorption by PS-M-B were calculated using following equations:

$$R(\%) = \frac{C_i - C_f}{C_i} * 100\% \quad (1)$$

$$q_f = \frac{(C_i - C_f) * V}{m} \quad (2)$$

Where C_i and C_f are initial and measured (at specific time) concentration of PO_4^{3-}, respectively, V is the volume of the phosphate solution and m is the mass of the sorbent.
Experimental data from kinetic experiments were fitted using non-linear forms of two most frequently used kinetic reaction models: pseudo-first [11] and pseudo-second [12] order model.

RESULTS AND DISCUSSION

To explore the kinetic of the phosphate sorption onto biochar, the effect of the contact time onto PO_4^{3-} sorption by PS-M-B at various initial concentrations was examined at 25 °C, at solid/liquid ratio of 4 g/L and at initial pH=5.5 (which wasn't kept constant during the experiments) for different time intervals. It is interesting to notify that the final values of pH were higher than 10 for all concentrations investigated, indicating base nature of the sorbent and preferable medium for formation of the minerals (such as struvite) which is beneficial for phosphate removal. As can be seen in Figure 1, the rapid growth of the sorption capacity in the first 30 min was probably due to the high mass transfer and sufficient number of surface sorption sites, which suggested that there is a strong association between phosphate ions and PS-M-B surface. When these sites become saturated, the sorption tended to stabilize with a stable amount of phosphates bonded after only 3 h. The residual concentrations of phosphates were measured in regular intervals, up to 24 h, and remained constant in the whole time range (these data are not presented at the Figure 1) This indicate that the kinetic was fast in whole concentration range and that after saturation there are no desorption of bonded phosphates. The rapid initial sorption might be due to the electrostatic attraction between the positive

charged MgO deposited at the surface (during pretreatment (with $MgCl_2$) and pyrolysis) and the negative charged phosphate ions.
In the same time, lower initial concentrations were removed for shorter time: e.g. for initial phosphate concentration of 50 mg/L equilibrium was established after 120 min with removal efficiency (R) of 98%, while for the highest concentration of phosphates (200 g/L) the equilibrium was achieved after 4 h with the same removal efficiency. After 24 h of contact, 100% of removal efficiency was established for all concentrations. The experimental equilibrium capacities (under previously defined operational parameters) were found to be almost 12 mg/g ($Ci(PO_4^3)$ = 50 mg/L) and 48 mg/g (($Ci(PO_4^{3-})$ = 200 mg/L).

Experimental data obtained through the batch sorption experiments were fitted by previously mentioned models and obtained curves are presented at Figure1.

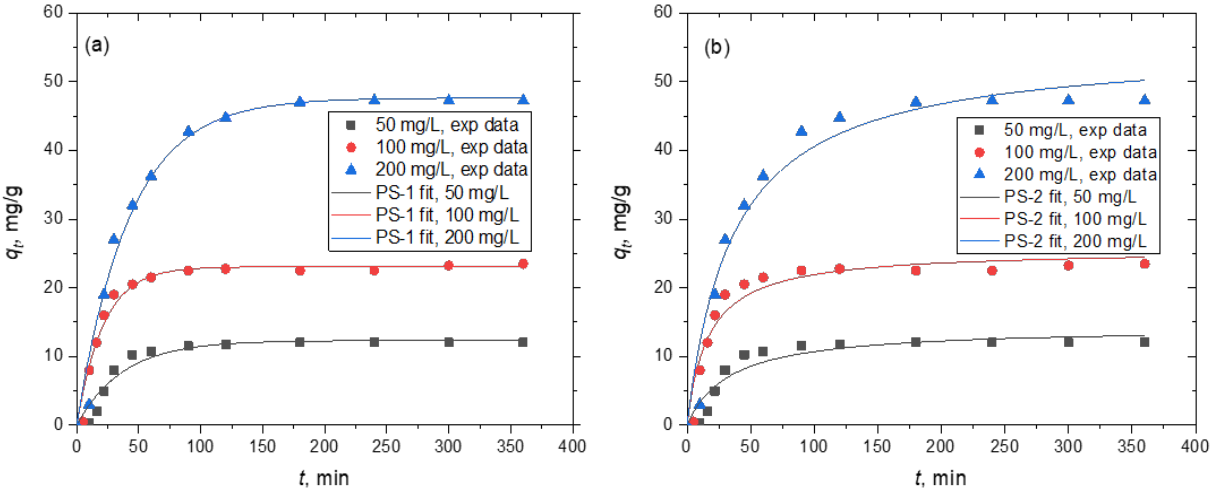


Fig. 1. *Fitting of experimental data by (a) pseudo-first model and (b) pseudo-second model*

Kinetic parameters for pseudo-first and pseudo-second order models are shown in Table 1. As it can be seen from Figure 1 and data presented in Table 1, the pseudo-second order model fit well the sorption kinetics with R^2 ranging from almost 0.9 at the PO_4^{3-} concentration of 50 mg/L and 0.96 at PO_4^{3-} concentration of 200 mg/L. In opposite, the sorption kinetics obeyed pseudo-first order model very well with R^2 higher than 0.93 in whole concentration range. In the same time, statistical parameter of model fitting, χ^2, was lower for pseudo-first than for pseudo-second order. The predicted values of the pseudo-first order were 12.3, 23.1 and 47.7 mg/g respectively for the sorption of 50, 100 and 200 mg/L of initial phosphate concentrations, and very close to the experimental values (q_{exp}) shown in Table 1.

Table 1. *Kinetic parameters for phosphate sorption by PS-M-B fitted by PS-1 and PS-2*

Model		Initial phosphate concentration, mg/L		
		50	**100**	**200**
	q_{exp}, mg/g	**12.0**	**23.5**	**48.0**
PS-1	q_1, mg/g	12.3	23.1	47.7
	k_1 (1/min)	0.027	0.045	0.024
	R^2	0.934	0.974	0.982
	χ^2	1.617	1.998	5.896
PS-2	q_2, mg/g	14.3	25.6	55.2
	k_2 (g/(mg min))	0.0021	0.0023	0.0005
	R^2	0.895	0.943	0.962
	χ^2	2.590	4.318	12.37

The results presented in Table 1 indicate that the pseudo-first-order model fits better removal of phosphates by biochar made from modified peach stone particles, suggesting that phosphate uptake may be driven more by physical adsorption (e.g., van der Waals forces or electrostatic interactions) than chemical bonding. This is interesting, since the most of the literately available data indicate that the pseudo-second order model better describes phosphate bonding by metal loaded biochars, suggesting the chemisorption as possible mechanism [10, 13]. The results of Karunanithi et al. [14] also indicate that sorption of phosphates by biochar derived from soybean stover was mainly a physisorption process, which was further substantiated through the absence of any additional chemical bond formation through FT-IR spectra and negligible phase change through XRD data. However, the pseudo-second-order model still shows a strong fit, so chemisorption can't be ruled out entirely. Thus, the phosphate sorption onto biochar is controlled by the synergistic interaction of many mechanisms, from physical to chemical capture mechanisms, where the physical sorption is associated with the structure and surface area of BC, while the chemical is associated with the biochar type and the number and type of present functional groups [15].

CONCLUSION

The kinetic of sorption performances of phosphate onto Mg modified biochar composite was investigated in this paper with the aim of elucidating necessary time for reaching equilibrium in wide concentration range. It was concluded that the mechanism of the removal process is combination of phisi and chemisorption process, and that further analyses are required, In the same time, synthetized sorbent have shown high removal efficiency in the whole concentration range, acting as promising material for phosphate removal from contaminated water streams. These results suggest that 20% PS-M-B composite has great potential to be used for removal of phosphate from this nutrient-rich surface waterbodies. It should be also underlined that the application of this sorbent is very attractive from both environmental and economic aspects, since the low-cost waste biomass readily available and could be obtained in large quantities from local producers. Unfortunately, current practice is to deposit this organic waste at open landfills, which represents significant resource losses and air quality concerns. Therefore, the thermochemical conversion of these biomass wastes into useful products support not only the reduction of greenhouse gasses emission but also improves the disposal strategy of agricultural solid waste disposal.

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REFERENCES

[1] Uday, V., Harikrishnan, P.S., Deoli, K., Zitouni, F., Mahlknecht, J., Kumar, M.: Current trends in production, morphology, and real-world environmental applications of biochar for the promotion of sustainability, Bioresource Technology, Vol. 359, p. 127467, 2022.

[2] Gabhane, J.W., Bhange, V.P., Patil, P.D., Bankar, S.T., Kumar, S.: Recent trends in biochar production methods and its application as a soil health conditioner: a review. SN Applied Science, Vol. 2, p. 1307, 2020.

[3] Panić, S., Đurišić-Mladenović, N., Petronijević, M., Stijepović, I., Milanović, M., Kozma, G., Kukovecz, A.: Valorization of waste biomass towards biochar production

– Characterization and perspectives for sustainable applications in Serbia, Environmental Technology & Innovation, Vol. 37, p. 104043, 2025.

[4] Shanmugam, V., Sreenivasan, S.N., Mensah, R.A., F¨orsth, M., Sas, G., Hedenqvist, M.S., Neisiany, R.E., Tu, Y., Das, O.: A review on combustion and mechanical behavior of pyrolysis biochar, Materials Today Communications, Vol. 31, p. 103629, 2022.

[5] Kapoor, R.T., Ahmad, P., Rafatullah, M.: Insights into Biochar Applications: A Sustainable Strategy toward Carbon Neutrality and Circular Economy, Catalytic Applications of Biochar for Environmental Remediation: Sustainable Strategies Towards a Circular Economy, Vol. 2, pp. 1–30, 2024.

[6] Mei, Y., Zhuang, S., Wang, J.: Adsorption of heavy metals by biochar in aqueous solution: A review, Science of The Total Environment, Vol.968, p.178898, 2025.

[7] Marcińczyk, M., Sik Ok, Y., Oleszczuk, P.: From waste to fertilizer: Nutrient recovery from wastewater by pristine and engineered biochars, Chemosphere, Vol.306, p.135310, 2022.

[8] Murtaza, G., Ahmed, Z., Valipour, M., Ali, I., Usman, M., Iqbal, R., Zulfiqar, U., Rizwan, M., Mahmood, S., Ullah, A., Arslan, M., Rehman, M.H.U., Ditta, A., Tariq, A.: Recent trends and economic significance of modified/functionalized biochars for remediation of environmental pollutants. Scientific Reports, Vol.2, p. 217, 2024.

[9] Aljeboree, A.M., Alshirifi, A.N., Alkaim, A.F.: Kinetics and equilibrium study for the adsorption of textile dyes on coconut shell activated carbon, Arabian Journal of Chemistry, Vol.10, pp 3381–93, 2017.

[10] Li, H., Dong,X., da Silva, EB., de Oliveira, LM., Chen, Y., Ma, LQ.: Mechanisms of metal sorption by biochars: biochar characteristics and modifications, Chemosphere, Vol.178, pp. 466-478, 2017.

[11] Lagergren S.: About the theory of so called adsorption of soluble substances. Svenska Vetenskapsakademiens Handlingar, Vol. 24, pp. 1-39, 1898.

[12] Ho, Y.S., McKay, G.: Pseudo-second order model for sorption processes. Process Biochemistry, Vol.34, pp 451-465, 1999.

[13] Li, R., Wang, J., Zhou, B., Zhang, Z., Liu, S., Lei, S., Xiao,R.:Simultaneous capture removal of phosphate, ammonium and organic substances by MgO impregnated biochar and its potential use in swine wastewater treatment, Journal of Cleaner Production,, Vol.147, pp.96-107, 2017.

[14] Karunanithi, R., Sik Ok, Y., Dharmarajan, R., Ahmad, M., Seshadri, B., Bolan, N., Naidu, R.: Sorption, kinetics and thermodynamics of phosphate sorption onto soybean stover derived biochar, Environmental Technology and Innovation, Vol.8, pp. 113-125, 2017.

[15] Dai, Y., Wang, W., Lu, L., Yan, L., Yu, D.: Utilization of biochar for the removal of nitrogen and phosphorus, Journal of Cleaner Production, Vol. 257, p. 120573, 2020.



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MULTICRITERIA ANALYSIS OF OCCUPATIONAL HAZARDS IN UNDERGROUND MINING

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Abstract: Underground mining remains one of the most hazardous industries globally, exposing workers to a wide range of geo-mechanical, chemical, and ergonomic risks. This study systematically classifies occupational hazards—such as traumatic injuries, respiratory conditions, and musculoskeletal disorders—and evaluates evidence-based prevention strategies. The Analytic Hierarchy Process (AHP), a multi criteria decision-making (MCDM) method, is employed to assess and prioritize these hazards and the corresponding mitigation measures. The findings identify the most critical risks, including roof collapses, gas explosions, and dust exposure, and evaluate the effectiveness of various control strategies. The study offers practical insights for improving safety management in underground mining and underscores the importance of structured decision-making in hazard prevention.
Key words: occupational hazards, underground mining, AHP, safety management, prevention strategies.

INTRODUCTION

Underground mining remains one of the most hazardous industrial sectors due to the complex and dynamic nature of the working environment characterized by confined spaces, unstable geological conditions, exposure to harmful substances, and heavy machinery. Workers are exposed to multiple risks, including rock falls, gas explosions, poor ventilation, and ergonomic injuries. Globally, mining accounts for 1% of the workforce but 8% of fatal occupational injuries. Despite advancements in safety technologies and regulatory frameworks, mining accidents and occupational diseases continue to occur, leading to fatalities, long-term disabilities, and substantial economic losses [1-3]. To address these challenges, a systematic and multi criteria approach is essential for evaluating risks, prioritizing hazards, and implementing effective prevention strategies.
Traditional risk assessment methods often fail to capture the interdependencies between different hazards, necessitating a structured multi criteria approach.
The Analytic Hierarchy Process (AHP) is a robust MCDM technique that decomposes complex problems into hierarchical structures, allowing for pairwise comparisons of criteria and alternatives [4]. This paper applies AHP to:

- identify and prioritize key occupational hazards in underground mining,
- evaluate prevention strategies based on feasibility and effectiveness, and
- provide a decision-support framework for safety management in mining operations.

By analyzing various risk parameters, such as likelihood, severity, exposure frequency, and mitigation feasibility, this research aims to identify high-priority hazards and propose targeted prevention measures. The findings will contribute to enhancing safety protocols, and fostering a safer working environment for miners. Ultimately, this paper seeks to bridge the gap between theoretical risk assessments and practical safety interventions, providing actionable insights for mining companies, policymakers, and occupational health professionals.
For this reason, a multi-criteria analysis of the most important occupational hazards in underground mining was carried out in this paper, and general prevention measures in mining and in particular the prevention of injuries in underground mining were defined.
Many studies demonstrate effectiveness of AHP method in ranking safety interventions in mining [5].

MATERIAL AND METHODS

The original methodology is determined to achieve optimal results. The working methodology defined by the author is shown in Fig. 1.
Fig. 1 shows that the research begins with the process of identifying the groups of occupation hazards in underground mining. The methods were identified based on a literature review and on the data from underground mining companies in our country.

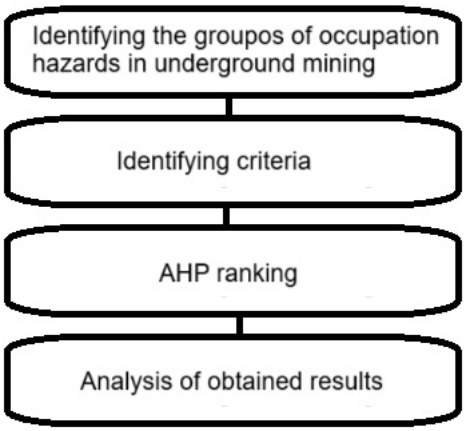


Fig. 1. *Schematic presentation of the work methodology*

In the next phase, the criteria were defined mainly on the basis of a literature review, but also on interview with mining experts and managers in our mines. The final list of groups of occupation hazards in underground mining and the criteria were finalised after these two phases.
Then the criteria were first ranked to identify the most influential criteria. The next step is to rank the groups of occupation hazards in underground mining. The AHP method was used for the ranking and the scores were given according to the group decision method (author with managers and experts from underground mines in the mines of our country).
Once the ranking list was drawn up, the results were analysed with the aim of identifying the most dangerous groups of occupational hazards in underground mining and determining general prevention measures in mining and, in particular, for the prevention of injuries in underground mining.

AHP METHOD

The Analytic Hierarchy Process (AHP) is a structured decision-making method. It helps to analyses complex decisions by breaking them down into a hierarchy of criteria and alternatives and then determining priorities through pairwise comparisons. The main theoretical principles of AHP include hierarchy building (decomposing the problem into a hierarchy of objectives, criteria, sub-criteria and alternatives), pairwise comparisons (comparing the elements at each level using a scale of 1-9 – Tab. 1.), calculation of priority vectors (using the eigenvector method to derive weights from the comparison matrix to ensure consistency), consistency checking (calculating the consistency ratio (CR) to ensure that the judgements are logically coherent (CR < 0.1 is acceptable)) and aggregation of weights (combining local priorities across the hierarchy to obtain global weights for alternatives).
AHP has many advantages, such as considering both qualitative and quantitative criteria and providing a systematic and transparent decision framework.
The main limitations are: Subjectivity in pairwise comparisons, can become complex with many criteria/alternatives.
AHP is used today in business, engineering, healthcare and politics for multi-criteria decision analysis.

Table 1. *AHP comparison scale*

Dominance	
Description	**Mark**
Equal	1
Weak dominance	3
Strong dominance	5
Very strong dominance	7
Absolute dominance	9
2, 4, 6, 8 are intermediate values	

RESULTS AND DISCUSSION

Identifying the groups of occupation hazards in underground mining

As previously noted, the categories of occupational hazards in underground mining were identified through a comprehensive literature review and consultations with mining experts in our country.
The most prevalent occupational hazards in underground mining, along with their descriptions, potential consequences, and recommended preventive measures, are outlined below:

- *Injuries caused by falling earth, stones and falling objects (Alternative A1)* – this hazard category includes impacts from fractured rocks, dropped tools, equipment, or loads during lifting operations. It accounts for approximately 34% of fatalities in underground mining. *Description*: collapse of pit walls, ceilings, or falling material from elevated areas. *Potential consequences*: severe physical trauma, bone fractures, and fatal injuries. *Preventive measures*: regular assessment of ground and structural stability, installation of appropriate support systems (e.g., rock bolts, mesh, piles), and strict adherence to safety protocols during excavation activities.
- *Injuries caused by handling heavy machinery (Alternative A2)* – this category encompasses injuries resulting from entrapment in moving machine parts (e.g., drills, conveyor belts), incidents involving tools or rock fragments during drilling, blasting, or transport, collisions with mining vehicles (e.g., locomotives, haul trucks), and accidents during loading or unloading operations. Conveyor belts and drilling equipment alone are responsible for approximately 22% of non-fatal injuries in underground mining. *Description*: injuries sustained during the operation of or proximity to heavy mining machinery, including excavators, drills, and conveyor systems. Potential consequences: amputations, contusions, bone fractures, and other serious injuries. *Preventive measures*: comprehensive worker training on equipment operation, routine maintenance of machinery, and consistent use of personal protective equipment (PPE).
- *Inhalation of harmful gases and dust (Alternative A3)* – this hazard includes exposure to respiratory dust (e.g., silica) and toxic gases (e.g., methane, carbon monoxide), leading to occupational diseases such as pneumoconiosis ("black lung"), silicosis, and other chronic respiratory conditions. Additional risks include noise-induced hearing loss and dermal or ocular damage from chemical agents. *Description*: prolonged or repeated exposure to airborne contaminants in confined underground environments. *Potential consequences*: chronic lung diseases (e.g., silicosis, pneumoconiosis), systemic poisoning, hearing loss, and chemical burns to the skin and eyes. *Preventive measures*: implementation of effective ventilation systems, continuous gas monitoring, use of respirators and filter-equipped masks, and application of wet drilling techniques, which can reduce airborne dust by up to 90%.
- *Explosions and burns (Alternative A4)* – this hazard involves burns and other injuries resulting from the detonation of explosives or accidental fires. Explosions may occur due to the accumulation of flammable gases such as methane or the improper handling of explosive materials. *Description*: high-energy incidents caused by gas build-up (e.g.,

methane) or misuse of explosives in confined underground environments. *Potential consequences*: thermal burns, traumatic injuries, and fatalities. *Preventive measures*: rigorous monitoring and control of methane concentrations, comprehensive training in explosive handling, and the use of antistatic equipment and spark-suppression systems.

- *Falls, slips and trips (Alternative A5)* – this category includes accidents caused by falling from heights (e.g., platforms, stairs, or unstable surfaces), slipping on wet or uneven terrain, or tripping over tools, cables, or mining equipment. *Description*: incidents typically occur during movement across wet, muddy, inclined, or obstructed surfaces within the underground work environment. *Potential consequences*: sprains, bone fractures, concussions, and other musculoskeletal injuries. *Preventive measures*: regular cleaning and maintenance of walkways, secure placement of equipment and materials, use of slip-resistant footwear, and clear marking of hazardous zones.
- *Injuries due to manual handling of loads, overexertion and poor working posture (Alternative A6)* – this hazard encompasses musculoskeletal disorders resulting from lifting, carrying, or moving heavy or awkwardly shaped loads without proper technique, as well as sustained poor posture during work activities. *Description*: physical strain caused by manual handling tasks performed without ergonomic consideration or mechanical assistance. *Potential consequences*: injuries to the spine, muscles, and joints, including chronic back pain and repetitive strain injuries. *Preventive measures*: training in proper lifting techniques, use of mechanical aids such as trolleys and cranes, and mechanization of manual tasks wherever feasible.

Identifying the criteria

The identification of criteria was based on a comprehensive literature review and interviews with mining experts and site managers from domestic mining operations. Four key criteria were identified as the most critical, namely:

- *Severity (Criteria C1)*: This criteria denotes the extent of harm or adverse impact that a hazard may inflict upon a worker's health or safety should an incident occur. It assesses the potential consequences, ranging from minor injuries to life-threatening conditions.
- *Frequency (Criteria C2)*: This criteria reflects the regularity with which workers are exposed to hazardous conditions, accidents, or occupational health risks in underground mining operations. It encompasses both acute incidents (e.g., roof collapses, explosions) and chronic health risks (e.g., respiratory diseases due to prolonged dust exposure).
- *Controllability (Criteria C3)*: This parameter evaluates the degree to which mining operators and workers can prevent, mitigate, or manage occupational hazards through engineered controls, administrative measures, safety protocols, and the use of personal protective equipment (PPE).
- *Economic impact (Criteria C4)*: This criteria refers to the direct and indirect financial repercussions of workplace accidents, injuries, illnesses, and fatalities on mining operations, stakeholders, and society at large. These impacts may manifest as immediate costs (e.g., emergency response and compensation) or long-term effects (e.g., diminished productivity due to chronic occupational diseases).

AHP ranking

Once all alternatives and criteria have been identified, the Analytic Hierarchy Process (AHP) method is applied. The ranking was conducted using the online AHP tool available on GitHub Pages (https://comcastsamples.github.io/ahp-tool). As previously stated, the objective is to rank occupational hazards in underground mining to support injury prevention efforts.
The ranking of the measures was carried out by managers and mining experts, as noted earlier. First, a pairwise comparison matrix for the criteria (Tab. 2) was established to determine

their relative influence on the final ranking of alternatives—occupational hazards in underground mining.

Table 2. *Comparison marks of criteria*

	C1	C2	C3	C4
C1	1	3	1/2	1
C2		1	1/5	1/5
C3			1	1/2
C4				1

Following the calculations, the weighting coefficients for the criteria were derived based on the pairwise comparison scores presented in Tab. 2 (results illustrated in Figure 2).

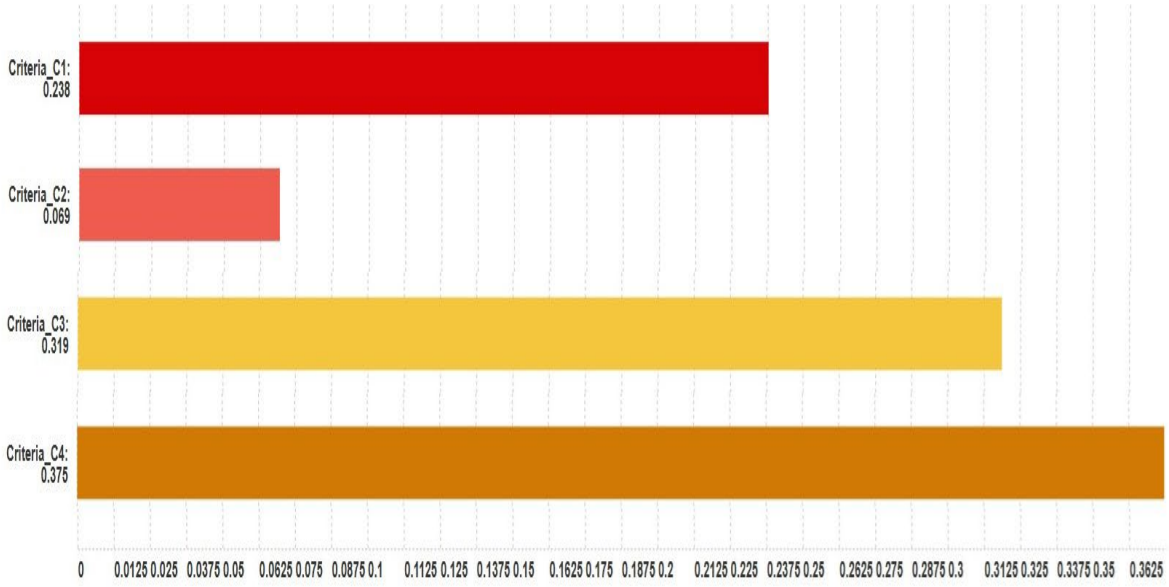


Fig. 2. *The obtained weighting coefficients of the criteria*

Subsequently, the mining method groups (alternatives) were evaluated against each of the four predefined criteria, as detailed in Tables 3–6.

Table 3. *Comparison of the alternatives with respect to criteria C1*

	A1	A2	A3	A4	A5	A6
A1	1	1	3	1/3	4	6
A2		1	3	1/3	4	6
A3			1	1/6	2	3
A4				1	6	7
A5					1	1
A6						1

Table 4. *Comparison of the alternatives with respect to criteria C2*

	A1	A2	A3	A4	A5	A6
A1	1	1/2	1/5	1	1/3	1/5
A2		1	1/3	2	2	1
A3			1	3	2	1
A4				1	1/3	1/5
A5					1	1/2
A6						1

Table 5. *Comparison of the alternatives with respect to criteria C3*

	A1	**A2**	**A3**	**A4**	**A5**	**A6**
A1	1	2	1	1/3	2	1
A2		1	1/3	2	1	1/2
A3			1	3	2	3
A4				1	1/3	1/4
A5					1	1
A6						1

Table 6. *Comparison of the alternatives with respect to criteria C4*

	A1	**A2**	**A3**	**A4**	**A5**	**A6**
A1	1	4	5	1/2	5	5
A2		1	2	1/6	2	4
A3			1	1/6	1	2
A4				1	5	7
A5					1	2
A6						1

Finally, the ranking results for the alternatives were determined, as presented in Fig. 3.

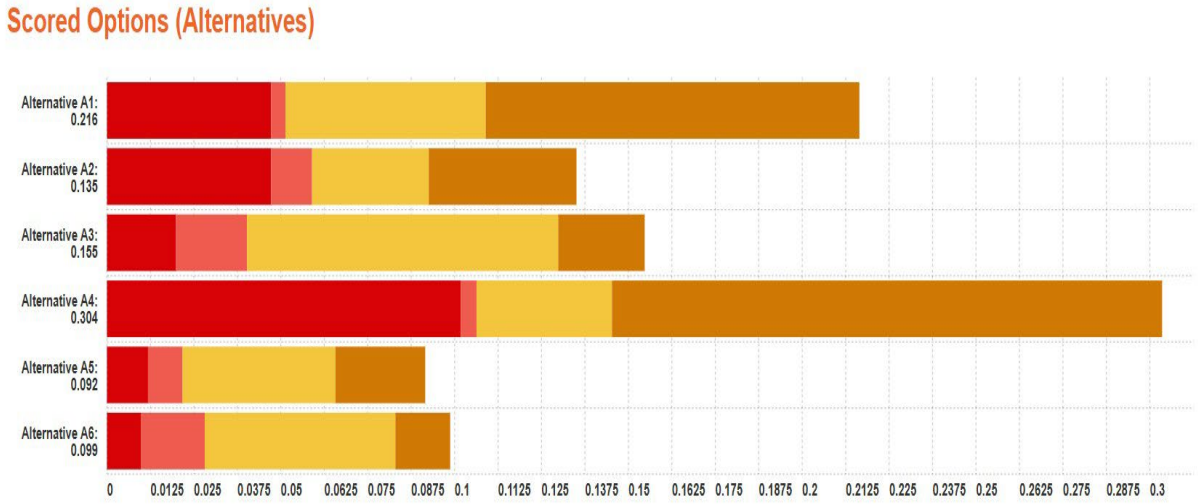


Fig. 3. *The obtained final rank of the alternatives*

Analysis of obtained results

The analysis incorporates both the evaluation criteria and their respective impacts on the ranking outcomes, along with the alternatives (occupational hazards in underground mining). Regarding the criteria analysis, particular attention is given to their weighting coefficients, which quantitatively represent each criteria's relative influence on the final ranking of alternatives.

From Fig. 2., it is evident that criteria C4 (economic impact) exerts the greatest influence on the ranking results, with a weighting coefficient of 0.375. This indicates that direct and indirect financial consequences have the most significant effect on mining companies in terms of occupational hazards. Such economic losses impact all stakeholders within mining operations, from individual workers to the organization as a whole.

Criteria C3 (controllability) ranks second. This factor reflects the capacity to manage and mitigate occupational hazards, highlighting the potential to reduce or even eliminate many adverse incidents.

Criteria C1 (severity) occupies the third position. This is a critical factor, as severe injuries, occupational diseases, and fatalities occur at a considerably higher rate in underground mining compared to other industries.
Finally, criteria C2 (frequency) ranks last. Despite its position, it remains a key parameter, as it reflects how often occupational hazards materialize. The frequency of such hazards serves as an essential indicator in identifying the most severe risks.
Regarding the occupational hazards (alternatives) presented in Fig. 3, the most severe is A4 (explosions and burns). This hazard is characterized by a high number of worker injuries and fatalities, miners being trapped underground, and significant economic and material losses. In some cases, such incidents have led to permanent mine closures—for example, the Aleksinac coal mine in Serbia.
Ranking second is alternative A1 (injuries caused by falling earth, rocks, and collapsing structures). These hazards also pose serious risks, frequently resulting in severe injuries, fatalities, and substantial material damage. Moreover, they often cause prolonged or even indefinite operational disruptions in affected sections of underground mines.
Alternative A3 (inhalation of harmful gases and dust) occupies third place. These hazards contribute to chronic occupational diseases, long-term disability, and, in extreme cases, fatalities among severely affected workers.
In fourth place is alternative A2 (injuries caused by handling heavy machinery). Modern underground mining relies heavily on mechanized equipment, which, while improving efficiency, also increases the risk of severe and sometimes fatal worker injuries. Additionally, prolonged exposure to machinery-related hazards—such as noise and vibration—can lead to occupational illnesses.
Alternative A6 (injuries due to manual handling of loads, overexertion and poor working posture) ranks fifth. Despite advances in mechanization, mining remains labor-intensive compared to other industries. Cramped workspaces, high temperatures, poor ventilation, and the physical demands of manual loading and unloading contribute to musculoskeletal injuries and long-term disabilities.
Finally, alternative A5 (falls, slips, and trips) is ranked last. Uneven terrain, water accumulation, mud, and confined spaces create hazardous conditions that frequently lead to worker injuries from falls and slips.
Occupational safety management in underground mining encompasses two key categories of interventions: general safety measures and injury prevention strategies.
General Safety Measures – these measures establish a foundational safety framework and include:

- Training and education: Regular and comprehensive instruction on occupational health and safety protocols to ensure worker competency.
- Personal protective equipment (PPE): Mandatory use of helmets, safety goggles, gloves, reinforced footwear, high-visibility clothing, and respirators to mitigate exposure to hazards.
- Inspection and maintenance: Systematic technical evaluations of mining equipment and infrastructure to ensure operational integrity.
- Emergency preparedness: Clearly defined evacuation plans, marked escape routes, and readily available fire suppression systems.
- Health surveillance: Periodic medical examinations and continuous monitoring of workers' health to detect occupational illnesses early.
- Safety culture promotion: Encouraging transparent reporting of unsafe conditions and near-miss incidents to foster proactive hazard mitigation.

Injury Prevention Strategies – these targeted interventions aim to reduce workplace accidents and include:

- Continuous safety training: Reinforcement of hazard awareness and safe work practices.
- Strict PPE compliance: Enforcement of protective gear usage (e.g., helmets, respirators, impact-resistant footwear).

- Machinery upkeep: Preventive maintenance and timely repairs of mining equipment to minimize mechanical failures.
- Geotechnical monitoring: Regular assessment of rock stability combined with adequate roof and wall support systems.
- Atmospheric control: Real-time gas detection and effective ventilation to prevent toxic exposure and explosions.

Given that mining remains one of the world's most dangerous professions, the rigorous implementation of these measures is critical to reducing occupational risks and safeguarding worker well-being.

CONCLUSION

In this article, the Analytic Hierarchy Process (AHP) method was applied to rank occupational hazards in underground mining. The analysis considered the most prevalent hazards in this sector, together with their definitions, potential consequences, and recommended preventive measures. The hazards evaluated included: injuries caused by falling earth, stones, and other objects (Alternative A1); injuries resulting from the operation of heavy machinery (Alternative A2); inhalation of harmful gases and dust (Alternative A3); explosions and burns (Alternative A4); falls, slips, and trips (Alternative A5); and injuries arising from manual handling of loads, overexertion, and poor working posture (Alternative A6).

The ranking was conducted according to four criteria: severity (Criteria C1), frequency (Criteria C2), controllability (Criteria C3), and economic impact (Criteria C4). The AHP results identified explosions and burns (Alternative A4) as the most hazardous occupational risk. Among the criteria, economic impact (Criteria C4) exerted the greatest influence on the overall ranking of hazards.

The study further outlines key preventive measures in occupational safety management, emphasizing both general safety protocols and specific strategies for injury prevention.

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REFERENCES

[1] Baghaei Naeini, S. A., Badri, A., Identification and categorization of hazards in the mining industry: A systematic review of the literature. International Review of Applied Sciences and Engineering, Vol. 15, No. 1, pp. 1-19, 2024.
[2] Cliff, D., OHS in the Mining Industry in the 21st Century. University of Wollongong. Conference contribution, 2016.
[3] Elenge, M.M., De Brouwer, C., Identification of hazards in the workplaces of Artisanal mining in Katanga. IJOMEH, Vol.24, pp. 57–66, 2011.
[4] Saaty, T.L.: The Analytical Hierarchy Process, McGraw-Hill, New York, 1980.
[5] Nieto-Morote, A., Ruz-Vila, F., A fuzzy approach to construction project risk assessment. International Journal of Project Management, Vol. 19, No 2, pp. 220-231, 2011.

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OCCUPATIONAL HEALTH AND SAFETY RISK EVALUATION OF PM2.5 AIR POLLUTION DURING THE HEATING SEASON IN BELGRADE, SERBIA

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Abstract: Belgrade has faced persistent air pollution for decades, with particulate matter concentrations frequently exceeding World Health Organization (WHO) limits during the heating season. Among major pollutants, fine particulate matter smaller than 2.5 μm (PM2.5) poses particular risks to health and has gained increasing attention in occupational safety and health research. This study examined the frequency of low-wind-speed days and the distribution of PM2.5 concentrations under such conditions to assess monthly risk levels during the heating season. Results show that October, December, and January are periods of elevated occupational health and safety risk. These findings highlight the need for preventive measures, such as shorter outdoor shifts, increased rest breaks, and task rotation, to reduce worker exposure to hazardous PM2.5 levels.

Key words: risk, occupational safety and health, air pollution, pm2.5, heating season

INTRODUCTION

Air pollution represents one of the most serious public health challenges in modern urban environments. Consequently, all occupations predominantly performed outdoors are significantly affected. Fine particles with a diameter of less than 2.5 micrometers (PM2.5) are particularly dangerous, as their small size allows them to penetrate deep into the respiratory system and enter the bloodstream, causing a wide range of adverse health effects. According to the World Health Organization (WHO) reports indicate that nearly the entire world's population (99%) lives in areas with air quality below recommended levels. Globally, air pollution ranks as the second most important risk factor for mortality and for deaths in children under five, following malnutrition. In 2021, it was linked to 8.1 million deaths, with 58% caused by PM2.5 exposure [1].

Among the cities in Serbia, Belgrade stands out as a critical hotspot. As the largest urban center and the main administrative, economic, and transportation hub of the country, the city faces serious air quality challenges. During the heating season, the intensive use of fossil fuels in individual boilers and thermal power plants significantly increases emissions of harmful substances. In addition, the specific meteorological conditions characteristic of Belgrade during the winter months further degrades air quality. High atmospheric pressure, weak winds, and frequent temperature inversions, which can extend up to 700 - 1000 meters in height, together with the occurrence of fog and light drizzle, represent the most unfavorable conditions from the standpoint of local air quality [2]. Such conditions lead to the retention of pollutants in the lower layers of the atmosphere and a significant increase in PM2.5 concentrations, which further elevates the health risk for various outdoor occupations, including construction workers, warehouse and logistics staff, maintenance crews and machinery operators in open-pit mines, etc.

The importance of focusing specifically on Belgrade is also confirmed by the results of the World Health Organization. According to a detailed analysis conducted in cooperation with domestic institutions, approximately 3,600 premature deaths are recorded annually in the 11 largest cities in Serbia due to exposure to PM2.5, with Belgrade alone accounting for as many as 1,796 cases – almost half of the total mortality [3]. This clearly indicates that Belgrade is the epicenter of the health burden associated with air pollution in the country.

Recent analyses provide a clearer picture of the health burden and pollution dynamics in the Serbian capital. On the one hand, evidence suggests that exposure to PM2.5 can be linked to

27.2% of ischemic heart disease cases and 19.4% of strokes, with concentrations ranging from an average of 14.8 μg/m³ to daily peaks of 365 μg/m³ [4]. On the other hand, this health impact is reinforced by findings that during the most extreme heating season episodes, PM2.5 concentrations rose to 250 μg/m³, far above the WHO guideline of 15 μg/m³, with some episodes persisting for months and keeping the outdoor occupations under continuous exposure [5].

That being said, all working environments are affected by elevated pollution levels during the heating season, particularly occupations performed outdoors. Therefore, this paper first reviews the relevant literature addressing this issue. It then introduces a unique risk assessment methodology that combines pollution and meteorological data, followed by a discussion of the results.

LITERATURE REVIEW

PM2.5 is widely recognized as one of the most harmful air pollutants, and numerous studies have evaluated its health risks. Urban studies in China indicate that chemical composition strongly influences health outcomes. For example, Chen et al. [6] assessed PM2.5-bound components over three years in Beijing and reported average concentrations of 82 μg/m³, corresponding to lifetime carcinogenic risks of 1.9×10^{-4} and hazard quotients of 18, well above acceptable thresholds, with arsenic and chromium (VI) as the main contributors. In another Chinese megacity, source-specific health risks were analyzed using Positive Matrix Factorization (PMF), showing that industrial emissions and coal combustion dominated carcinogenic risk, while traffic-related pollutants led to non-carcinogenic effects, with an overall hazard index of 1.35 [7]. A longer-term study in Jinan applied PMF with the RM-RA model to assess twelve PM2.5-bound metals, revealing that Cr and As exceeded safe thresholds for carcinogenic risk, whereas Mn and Cd drove non-carcinogenic effects [8]. Seasonal contrasts further highlight the impact of chemical composition: in Shijiazhuang, winter PM2.5 and trace metal concentrations were 1.04–1.60 and 1.44–1.97 times higher than in pre-heating periods, resulting in 1.08–1.42 times higher hazard quotients, with Mn, As, and Co as dominant risk drivers [9].

Focusing on occupational safety and health, similar safety principles apply across all outdoor working environments: exposure to PM2.5 should be avoided once concentrations exceed certain thresholds. Accordingly, occupational settings should aim to minimize such exposure wherever possible. However, the nature of certain jobs makes this goal challenging. For example, a study by Yang et al. [10] found that construction workers are exposed to elevated PM10 and PM2.5 concentrations, with pit bottom workers, plasterers, masonry, and putty workers facing the highest occupational health risks. Using health risk assessment and monetization, the study highlighted the urgent need for improved dust control, ventilation, and protective measures on construction sites. Similarly, Shezi et al. [11] assessed occupational exposure to fine particulate matter (PM4 and PM2.5) among artisanal cookware makers in South Africa, finding notably high levels, especially at the workers' breathing zones. Finally, research by Lestari and Wandy [12] shifted the focus to the relationship between particulate matter levels in different occupational environments and weather conditions. It concluded that rain reduces PM2.5 concentrations both indoors and outdoors and highlighted the importance of accurate data analysis and visualization for Occupational Health and Safety management.

Despite these findings, few studies have quantitatively evaluated the influence of meteorological factors, such as wind speed, during the heating season. This study addresses that gap by proposing a quantitative framework for occupational health and safety (OHS) risk assessment related to PM2.5 exposure during the heating season in Belgrade. The findings may provide a foundation for future research and inform the development of public policy measures aimed at improving air quality and protecting workers' health.

METHODOLOGY

The core idea behind this research lies in creating a methodology which will be used to quantitatively assess the OHS risk which comes along with high PM2.5 air pollution in Belgrade, Serbia. More specifically, pollution data during the critical periods of the heating season will be analyzed and each month will be treated separately. The risk will be perceived as a product of two components: probability of an unwanted event occurring and the severity of consequences it generates. By intuition, there seems to be an obvious relationship between overall wind speed in a specific area and PM2.5 levels. Therefore, the following work will perceive the day with a low average wind speed as an unwanted event. Firstly, the goal is to statistically determine the correlation between the pollution and wind speed and to calculate daily average 'low' wind speed based on the corresponding air pollution threshold. This enables identifying the days that are of interest. Secondly, the probability of such a day occurring will be calculated, which will present the first risk component. Third part of the research will include analyzing the behavior of pollutants during unwanted events by determining the statistical distributions for each month. Fitting the data with distributions will enable extracting expected values which will present the second risk component – severity of the consequences. Finally, risk for each month will be calculated and evaluated inside a 5x5 risk assessment matrix with cautionary statements for each risk category. For this specific research, the data includes the heating seasons during the period 2018-2022 from a measuring station "Novi Beograd" provided by the Serbian Environmental Protection Agency in Belgrade, Serbia.

RESULTS AND DISCUSSION

Determination of a low average wind speed threshold

The necessary prerequisite for further analysis was proving that there is a dependency between daily average PM2.5 levels and daily average wind speed. Since the data is not normally distributed, the adequate parameter for measuring correlation is Spearman's correlation coefficient (ρ). The calculations showed a significant value of the coefficient $\rho=-0.69$, indicating a strong correlation between two variables.
Next step was approximating data with a function which fits it best. The results of the regression analysis have revealed that the function which explains the dependency most accurately is a power function shown in the Equation 1. The value of the coefficient of determination $R^2=0.402$ indicates that the generated function moderately approximates the data, as it is shown in Figure 1.

$$f(x) = 234.43 \cdot x^{-0.86} \quad (1)$$

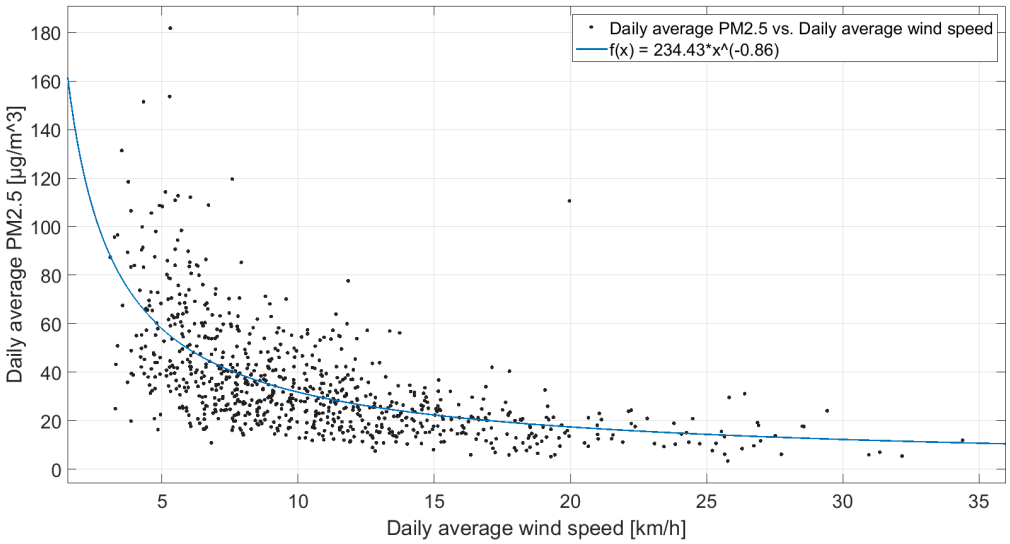


Fig. 1. *Fitted regression function and empirical data*

The generated regression function enabled the determination of a 'low' wind speed threshold. Following the Technical Assistance Document for the Reporting of Daily Air Quality by U.S. Environmental Protection Agency – USEPA [13], the limit for moderate air quality when it comes to PM2.5 is 35.5 µg/m^3 of a daily average and everything above that is considered unhealthy. The average wind speed threshold will be calculated by simply extracting the *x* from the function, for a given *f(x)*, as it is shown in Equation 2.

$$35.5 = 234.43 \cdot x^{-0.86} \rightarrow x = \left(\frac{35.5}{234.43}\right)^{\frac{-1}{0.86}} \approx 9 \quad (2)$$

Therefore, each day which had an average wind speed less than 9 km/h was considered 'an unwanted event'.

Frequency of days with average wind speed below the threshold

The initial dataset had covered the heating seasons (15th October to 15th April) from 2018 to 2022. Subsequently, for each month, the days of interest were counted, and the probability parameter was calculated based on their relative proportion of the total period (Table 1).

Table 1. *The probability of occurence for each month*

Month	Measurement period 2018-2022 [days] (d_a)	'Low' wind speed periods [days] (d_{lws})	Probability of occurrence ($p = d_{lws}/d_a$)
October (2nd half)	85	58	0.682
November	150	74	0.493
December	155	72	0.464
January	155	72	0.464
February	141	53	0.376
March	155	63	0.406
April (1st half)	75	29	0.387

Statistical testing of PM2.5 level distributions

Further analysis has filtered the initial dataset according to the calculated wind speed threshold. Given that the current day had been considered an 'unwanted event', the goal was

to determine which statistical distribution best fits the pollution data during such events. Eventually, the extraction of expected values from each theoretical distribution enabled the creation of the second risk parameter, which will present the rank of the consequences an unwanted event generates. The results of the Kolmogorov–Smirnov test indicated that hourly values of PM2.5 levels during the days when the average wind speed is low can be approximated by the Gamma theoretical distribution, with 95% confidence (α=0.05). The theoretical cumulative distribution function (CDF) is given in Equation 3 [14], whereas the results of testing with the parameters of fitted functions are given inside Table 2.

$$F(x;a,b) = \frac{\gamma(a,\frac{x}{b})}{\Gamma(a)} = \frac{\int_0^{x/b} t^{a-1}\, e^{-t} dt}{\int_0^{\infty} t^{a-1}\, e^{-t} dt} \tag{3}$$

The visual representations of KS testing are given through empirical and theoretical fitted Gamma CDFs, in Figure 2. Besides that, Figure 3 shows the probability density functions (PDFs) and the movements of expected values with different periods of the year.

Table 2. *The results of KS statistical testing and parameters of the Gamma distribution*

x		p value	KS score	a	b	E(x)	V(x)
PM2.5 (μg/m^3)	October (2nd half)	0.075	0.035	2.773	14.882	41.263	614.065
	November	0.702	0.017	4.190	8.928	37.411	334.018
	December	0.070	0.033	2.850	20.580	58.655	1207.130
	January	0.131	0.031	3.482	18.381	64.013	1176.648
	February	0.439	0.027	2.590	20.235	52.405	1060.427
	March	0.186	0.030	2.886	13.531	39.055	528.467
	April (1st half)	0.266	0.042	3.482	7.448	25.938	193.197

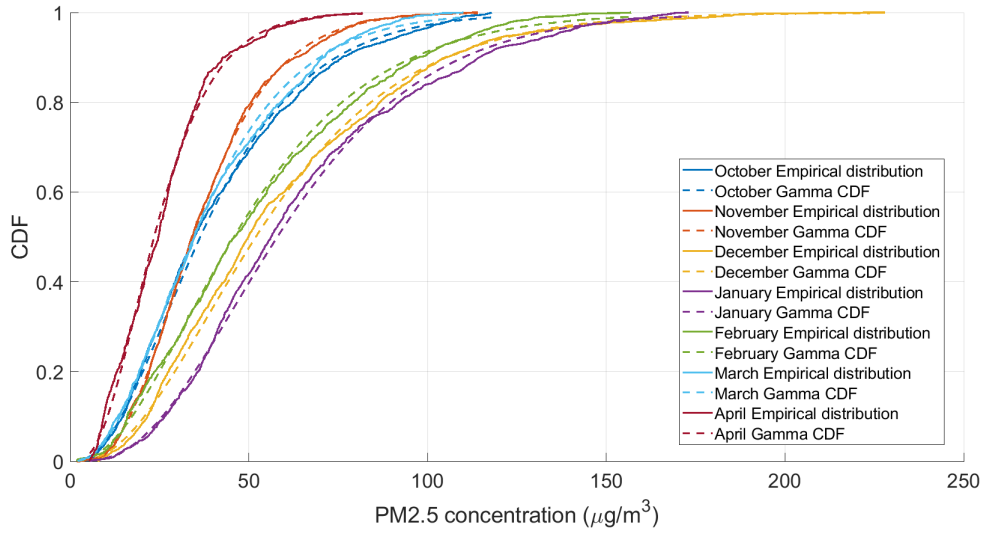


Fig. 2. *Empirical data and theoretical Gamma CDFs for each month during the heating season*

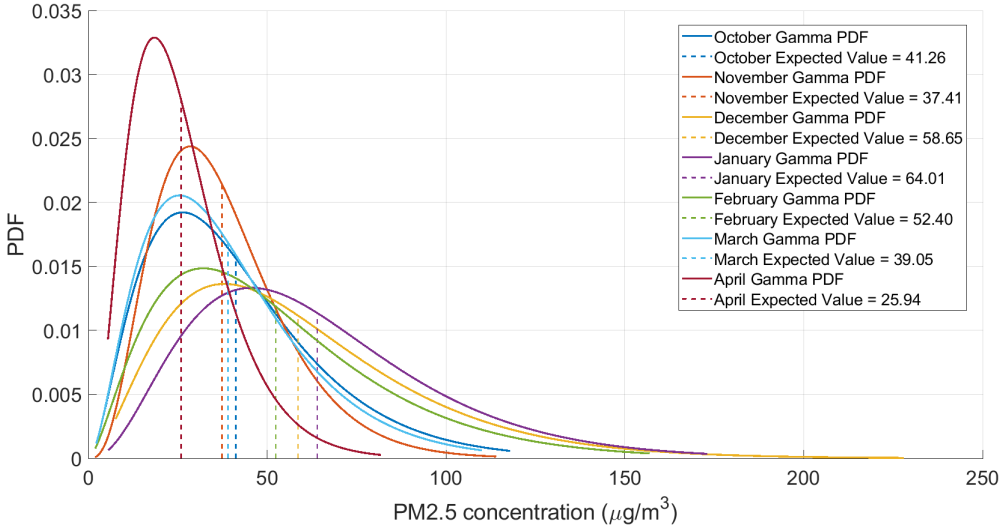


Fig. 3. *Theoretical Gamma PDFs for each month during with their expected values*

Risk evaluation model

The most basic risk evaluation models perceive risk as a measure of the probability and severity of adverse effects. In other words, risk is the product of the likelihood of an event occurring and its consequences which go along [15]. Therefore, the following assessment framework did not deviate from such approach, as final risk is calculated following Equation 4.

$$R = Likelihood \cdot Severity \tag{4}$$

The first component is evaluated with accordance to relative frequency of events during each month, respecting the defined categories in Table 3.

Table 3. *Likelihood of occurence evaluation*

Criterion	Likelihood	Rank
$p \leq 0.2$	Very Low	1
$0.2 < p \leq 0.4$	Low	2
$0.4 < p \leq 0.6$	Medium	3
$0.6 < p \leq 0.8$	High	4
$p > 0.8$	Very High	5

The second component of the product is the severity of consequences. Following the Air Quality Index categories outlined in the USEPA's technical assistance document [13], five severity labels were created.

Table 4. *Severity of consequences evaluation*

Criterion	AQI category	Severity	Rank
$PM2.5 \leq 9\ [\frac{\mu g}{m^3}]$	Good	Very Low	1
$9.1 \leq PM2.5 \leq 35.4\ [\frac{\mu g}{m^3}]$	Moderate	Low	2
$35.5 \leq PM2.5 \leq 55.4\ [\frac{\mu g}{m^3}]$	Unhealthy for Sensitive groups	Medium	3
$55.5 \leq PM2.5 \leq 125.4\ [\frac{\mu g}{m^3}]$	Unhealthy	High	4
$PM2.5 \geq 125.5\ [\frac{\mu g}{m^3}]$	Very Unhealthy	Very High	5

Finally, risk results have been calculated for each month and presented in a 5×5 risk assessment matrix (Figure 4). The final risk categories and suggested actions were derived by following the guidance and standards published by the Washington State Department of Labor & Industries [16], and the cautionary statements by the U.S. Environmental Protection Agency [13] and the Government of Canada [17].

Table 5. *Risk categories interpretation*

Criterion	Risk level	Suggested actions
$1 \leq R \leq 4$	Low	Normal work can continue. Standard monitoring and awareness.
$5 \leq R \leq 10$	Moderate	Sensitive workers (with respiratory/cardiac conditions) should be identified. Employers should monitor exposure and ensure protective masks (e.g. N95/FFP2 respirators) are available.
$11 \leq R \leq 16$	High	Consider all of the above measures. Implement exposure controls, such as using filtered enclosures or vehicles, portable HEPA filters, relocating or rescheduling work to areas/times with lower PM2.5 levels, minimizing activities that generate extra dust or smoke, reducing work intensity, and allowing more rest breaks.
$17 \leq R \leq 25$	Very High	Consider all of the above measures. Suspend or reschedule strenuous outdoor activities. If PM2.5 exceeds extreme thresholds (e.g. 250 μg/m³), suspend outdoor work except for essential/emergency tasks with full PPE. Employers must ensure workers experiencing symptoms get immediate medical attention.

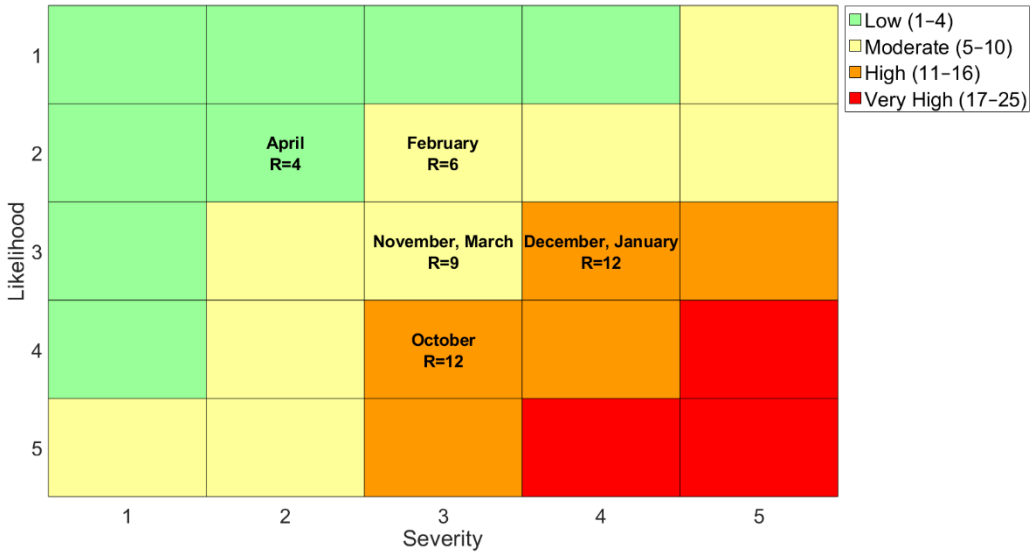


Fig. 4. *Risk visualization for each month in a 5x5 matrix*

CONCLUSION

This study aimed to quantitatively assess occupational safety and health risk associated with fine particulate matter during the heating season, focusing on days without meteorological phenomena that could act as natural urban air purifier. In particular, days with low average wind speed create conditions that allow particulate matter to accumulate in the lower atmosphere, making such events potentially hazardous from OHS risk mitigation perspective. Risk was defined as the product of the likelihood of such days occurring and the severity of their consequences. Scores were calculated separately for each month in the heating season and evaluated using a 5×5 risk assessment matrix. October had the highest probability of low-

wind days (relative share of 0.682 across the full measurement period), corresponding to rank 4 (high likelihood). On the other side, the severity of consequences was highest in December and January, where expected PM2.5 levels were 58.65 μg/m³ and 64.01 μg/m³, respectively (rank 4, indicating high severity). Overall, October, December, and January were classified as periods of high risk (R = 12), whereas April had the lowest risk score (R = 4). These evaluations were followed by practical occupational health and safety recommendations for companies operating in Belgrade, tailored to each month of the heating season.
Future research could diversify the data sources, i.e. use a greater number of monitoring stations which would provide a more realistic representation of air quality in Belgrade. In addition, the risk parameters could be estimated using more advanced approaches, such as simulation and/or different machine learning techniques. Eventually, it could be explored how this framework may be incorporated into intelligent air quality warning systems and adapted to other working environments with similar pollution and meteorological conditions (e.g. opencast mines). Given that occupational safety and health are fundamental, this study contributes by providing a methodological framework for assessing risks during periods of high air pollution, showing how established air quality indices within a risk matrix can offer a clear and actionable framework for communicating air pollution risks across diverse occupational environments.

AKNOWLEDGMENT

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REFERENCES

[1] IQAir, World air quality report 2024, 2025. Available at: https://www.iqair.com/newsroom/waqr-2024-pr
[2] Đurić, M. and Vujović D., Short-term forecasting of air pollution index in Belgrade, Serbia: *Meteorological Applications*, vol. 27, no. 5, p. e1946, 2020.
[3] World Health Organization, Health impact of ambient air pollution in Serbia: A call to action, WHO Regional Office for Europe, 2019. Available at: https://serbia.un.org/sites/default/files/2019-10/Health-impact-pollution-Serbia_0.pdf
[4] Cujic, M., Cirovic, Z., Djolic, M., Jankovic-Mandic, L., Radenkovic, M., Onjia, A., Assessment of the burden of disease due to PM2.5 air pollution for the Belgrade district: *Therm sci*, vol. 27, no. 3 Part B, pp. 2265–2273, 2023.
[5] Stanojević, G., Malinović-Milićević, S., Brđanin, E., Milanović, M., Radovanović, M., Popović, T., Impact of Domestic Heating on Air Pollution - Extreme Pollution Events in Serbia: *Sustainability*, vol. 16, no. 18, p. 7920, 2024.
[6] Zhang, T., Chen, Y., Xu, X., Health Risk Assessment of PM2.5-bound Components in Beijing, China during 2013–2015: *Aerosol Air Qual. Res.*, vol. 20, no. 9, pp. 1938–1949, 2020.
[7] Chen, R., Jia, B., Tian, Y., Feng, Y., Source-specific health risk assessment of PM2.5-bound heavy metals based on high time-resolved measurement in a Chinese megacity: insights into seasonal and diurnal variations: *Ecotoxicology and Environmental Safety*, vol. 216, p. 112167, 2021.
[8] Yang, D., Li, M., Geng, X., Feng, Z., Sources and Specified Health Risks of 12 PM2.5-Bound Metals in a Typical Air-Polluted City in Northern China during the 13th Five-Year Plan: *Toxics*, vol. 12, no. 8, p. 581, 2024.
[9] Ma, Q. *et al.*, Characteristics and Health Risks of Trace Metals in PM2.5 Before and During the Heating Period over Three Years in Shijiazhuang, China: *Toxics*, vol. 13, no. 4, p. 291, 2025.
[10] Yang, X., Yu, Q., Zhang, Y., Ma, W., Occupational health risk assessment of construction workers caused by particulate matter exposure on construction sites: *Heliyon*, vol. 9, no. 10, p. e20433, 2023.

[11] Shezi, B., Mathee, A., Cele, N., Ndabandaba, S., Street, R.A., Occupational Exposure to Fine Particulate Matter (PM4 and PM2.5) during Hand-Made Cookware Operation: Personal, Indoor and Outdoor Levels: *IJERPH*, vol. 17, no. 20, p. 7522, 2020.
[12] Lestari, T.E., Wandy, W., Relationship of PM2.5 Value between Rain-No Rain & Indoor-Outdoor on Occupational Health and Safety Information System Development (Study Case in East Bekasi, West Java - Indonesia): *INTEK : Jurnal Informatika dan Teknologi Informasi*, vol. 5, no. 2, pp. 51–56, 2022.
[13] United States Environmental Protection Agency, Technical assistance document for the reporting of daily air quality – the air quality index (AQI), Research Triangle Park, NC, 2024. Available at: https://document.airnow.gov/technical-assistance-document-for-the-reporting-of-daily-air-quailty.pdf
[14] Johnson, N.L., Kotz, S., Balakrishnan, N., Continuous Univariate Distributions, 2nd ed., vol. 1. New York, NY, USA: John Wiley & Sons, 1994.
[15] Aven, T., On how to define, understand and describe risk, *Reliability Engineering & System Safety*, vol. 95, no. 6, pp. 623–631, 2010.
[16] Wildfire Smoke: Washington State Department of Labor & Industries. Available at: https://www.lni.wa.gov/safety-health/safety-topics/topics/wildfire-smoke
[17] Understanding Air Quality Health Index messages. Government of Canada. Available at: https://www.canada.ca/en/environment-climate-change/services/air-quality-health-index/understanding-messages.html

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OPTIMIZING NOISE LEVELS IN A VEHICLE – CASE STUDY

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Abstract: This paper presents the problem of vehicle produced noise and explores ways to reduce that noise for the driver and the passengers of a common driven car on european roads, the Mazda 3 Hatchback from 2008. Using a sound level meter, it was measured acoustic levels at ear level for the driver and passengers of the car at different speeds and gears. The road type, weather conditions, tires and vehicle condition were unchanged in order not to influence the obtained results.

Key words: v*ehicle restauration, noise control, acoustic comfort*

INTRODUCTION

Noise measurement focuses on studying the intensity, frequency, and direction of sound, with particular attention to environmental and traffic-related sources. In urban areas, the widespread use of vehicles is a major contributor to noise pollution, which affects both pedestrians and drivers. Prolonged exposure to high noise levels can cause discomfort, stress, and even health problems such as hypertension or cardiovascular disease.
Traffic noise is regulated by European and national legislation, which sets maximum acceptable sound levels for different zones and times of day. However, in many cities these limits are often exceeded, especially in densely populated areas.
To improve comfort inside vehicles, modern manufacturers invest heavily in soundproofing technologies, while budget cars often rely on minimal insulation. Cabin noise typically enters through the floor, doors, roof, and wheel arches [1]. This paper investigates noise measurement and reduction in a widely used vehicle, aiming to demonstrate how modern soundproofing solutions can significantly enhance comfort in older models.
Recent advances in acoustic measurement technologies have expanded the ability to monitor and analyze vehicle noise in real time. For instance, sensor-based systems allow for the detection and characterization of sound sources with high precision, enabling researchers to assess how noise propagates both inside and outside a moving vehicle. Such systems provide valuable insights into the complex interaction between vehicle mechanics, road conditions, and surrounding environments, ultimately helping engineers design more effective noise-reduction strategies [2].
Another important aspect in the study of traffic-related noise is its impact on urban mobility and the quality of life of city residents. Research on transportation systems has shown that high noise levels from vehicles not only affect drivers but also lead to social dissatisfaction among communities exposed to constant traffic noise. This has significant implications for transport planning, as policymakers are encouraged to adopt strategies that mitigate the acoustic impact of road networks through infrastructural adjustments and vehicle-level solutions [3].
In addition to traffic noise in general, interior vehicle acoustics have become an area of increasing research interest. Studies have revealed that cabin noise depends heavily on the distribution of vibration across different car components, such as the body panels, suspension, and tires. Numerical simulations and experimental tests are often combined to identify the dominant vibration sources, enabling more effective soundproofing strategies. By reducing these structural vibrations, manufacturers can significantly improve acoustic comfort and overall driving experience [4].

A related stream of research has focused on the role of materials and insulation techniques in reducing vehicle cabin noise. Investigations have shown that using advanced composites and multilayer panels can drastically minimize noise transmission from the external environment to the passenger space. Furthermore, comparative studies between traditional and modern insulation materials highlight clear benefits in terms of both acoustic efficiency and weight reduction, which is crucial for maintaining fuel efficiency in vehicles [5].
Beyond passenger comfort, traffic-generated noise also represents a broader environmental concern. Research has highlighted that road noise contributes significantly to overall urban sound pollution, influencing not only human health but also urban ecosystems. Studies in this area emphasize that effective mitigation requires a combination of technological innovation at the vehicle level and broader policy measures aimed at reducing exposure in densely populated areas [6].
Finally, experimental approaches to noise evaluation demonstrate the importance of standardized methodologies for obtaining reliable results. Measurements conducted in controlled and real-world conditions underline the necessity of considering variables such as vehicle speed, type of road surface, and traffic density. These factors are essential for ensuring accurate comparisons between vehicles and for developing practical solutions that can be applied consistently across different contexts [7].

MATERIAL AND METHODS

The car used for soundproofing and measurements is a Mazda 3 Hatchback from 2008 since it is a common, affordable transportation solution for most people looking to buy a vehicle. Mazda always meant for the model to be a good and compact solution for lower budgets, so they made the car affordable leaving room for sound comfort improving. The cars engine, exhaust and chassis have not been modified prior to our soundproofing solution.
The gearbox comes with only 5 gears for moving forward, so driven at high speeds like 130 km/h keeps your engine at around 3500 RPM. In this situation the engine and exhaust produce a lot of noise that can't be avoided in the standard configuration.
Being a budget car also means that besides having too much noise in the cabin at higher speeds, comfort was not a priority, so unnecessary noise gets in the cabin even at lower speeds or even while idling.
The car is equipped with a 1.6 liter naturally aspirated engine making 105 hp at 6000 rpm. The chassis is built out of steel, having the following panel thicknesses:

- Side panels (doors), 0.7 mm – 1 mm,
- Floor, 1 mm – 1.5 mm,
- Structural components 1.2 mm – 2 mm +.



***Fig. 1**. Mazda 3 HatchBack 2008 [8]*

The decibel meter used in this work is DT-8852 made by CEM. This device was used to measure sound level inside the car for the driver and passengers. By recording the sound level in the car before and after our soundproofing procedure, an exact result of decibel reduction can be defined. The measurements are all taken at ear level for the driver, front passenger and rear passengers, all at different travel speeds and engine RPM according to speciffic gears.



Fig. 2. *DT-8852 made by CEM [9]*

The CEM DT-8852 is a high accuracy digital sound level meter used for environmental and quality control use, measuring from 30 dB up to 130dB with type 2 accuracy ± 1.4 dB.

Soundproofing the vehicle

For the procedure of soundproofing the main focus was on the doors and the floor of the car, since that is where most of the road noise comes through in the cabin.
The materials used are from STP and they have the role of absorbing vibration, improving thermal insulation, reducing noise and resonance in vehicles, while improving acoustic comfort and enhancing the performance of the car's audio system.

STP Bimast Bomb Premium is the vibration absorbing layer that needs to have first contact with the metal sheets. It is applied on a clean surface and needs to be heated up and rolled down with a special roller that makes sure the bond between this layer and the metal sheet is as good as possible.
It is made from butyl rubber, aluminum layers and adhesive backing, making a very efficient vibration absorbing and reducing resonance in metal panels while also adding about 2.38 kg with each sheet.



Fig. 3. *STP Bimast Bomb Premium [10]*

STP Accent 6 was designed to be used as layer you lay on top of vibration absorbing materials. It reduces noise and it also helps with the vibration damping of the first soundproofing layer.



Fig. 4. *STP ACCENT 6 [11]*

This material must be laid down as tight as possible, trying to not leave any gaps at all between the pieces. It is made from evenly foamed polyethylene with a partly ruptured closed cell structure.

STP Biplast 15 is made from open-cell polyurethane foam and is meant to be used for total coverage of parts by being very flexible. This layer is applied on the inside of door panels for noise reduction. In the front doors of the car, there were found materials similar to Biplast 15 that has the intent to reduce noise. The difference in technology and the fact the present solution will actually stick to each part of the door panel, will serve to reduce noise even further.



Fig. 5. *STP Biplast 15 [12]*

All the interior trim were removed, and also door pannels, floor carpet, accessories so there can exist good access to the sheets that were applied on. While soundproofing the car, the interest was to assure that there is no dust or oil on the surfaces where the materials were applied. The vibration absorbing sheets having a good bond with the metal sheet is crucial. Air bubbles can lead to corrosion in time and negatively influence the performance of all following materials.



Fig. 6. *Front door plastic cover with STP Biplast 15*

Through the installation there was found foam in the front door panels for noise reduction and a bit of vibration absorbing material on the floor of the car. Mazda focused on the most important spots in the car to apply their solutions to keep production and sale prices low.
With the materials applied to the car on the floor and on the interior of the doors, the next step was to record new sound levels and to test for improvements.

RESULTS AND DISCUSSION

The used sound level meter connects through a USB cable to a laptop that has installed the specific software application. Through the software, one can record live sound level data and have a live graph of dB / seconds generated. In figure 7 the recorded data can be observed for 0 km/h.

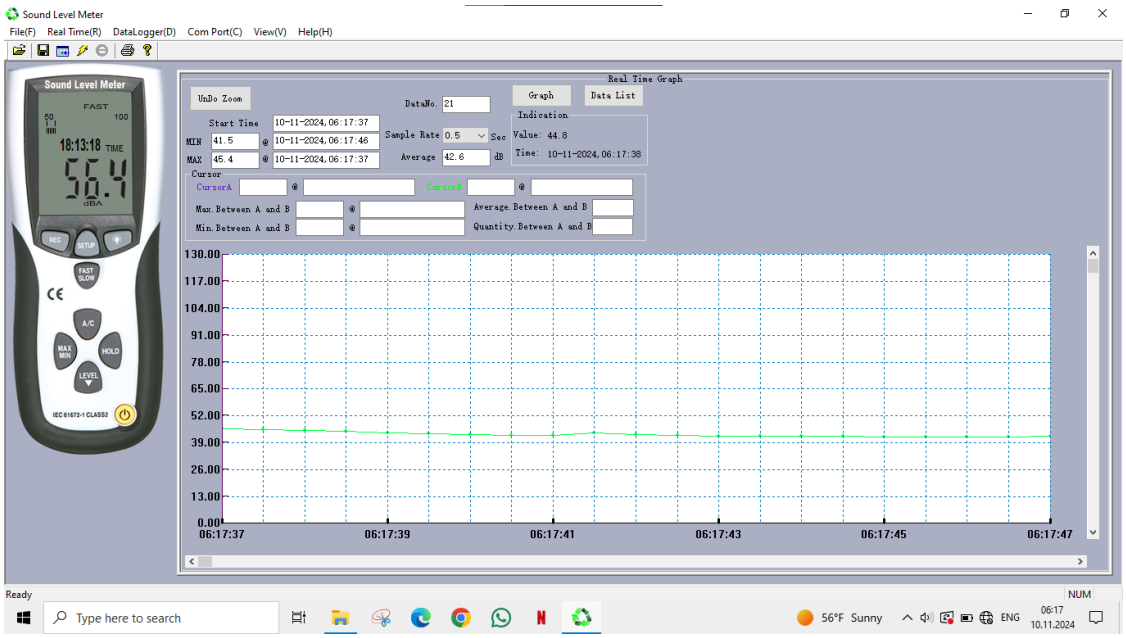


Fig. 7. Sound Level Meter Windows application

The measured sound levels were determined before and after soundproofing the car, in order to reduce the sound level medium measured in a 10 second period at different speeds. The speeds and gears chosen for measurements are the most common used in the city or outside the city:

- 0 km/h – neutral,
- 30 km/h – second gear,
- 50 km/h – third gear,
- 90 km/h – fourth gear,
- 110 km/h – fifth gear,
- 130 km/h – fifth gear.

From all the measurements one of the most representative for this car is the 130 km/h in fifth gear.

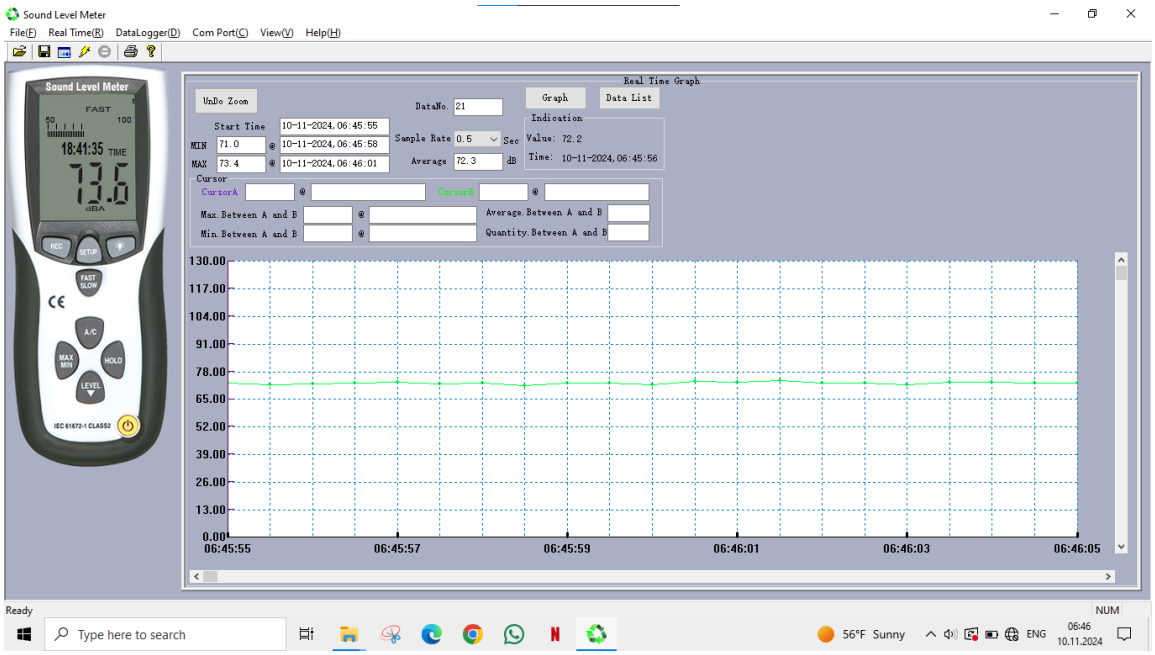


Fig. 8. Sound Level Meter measurement at 130 km/h in fifth gear before soundproofing

In figure 8 from above it can be observed a medium measurement of **72.3 dB** before soundproofing the car. This measurement was taken for the front passenger of the vehicle. The minimum recorded value in the 10 second period was **71 dB**.

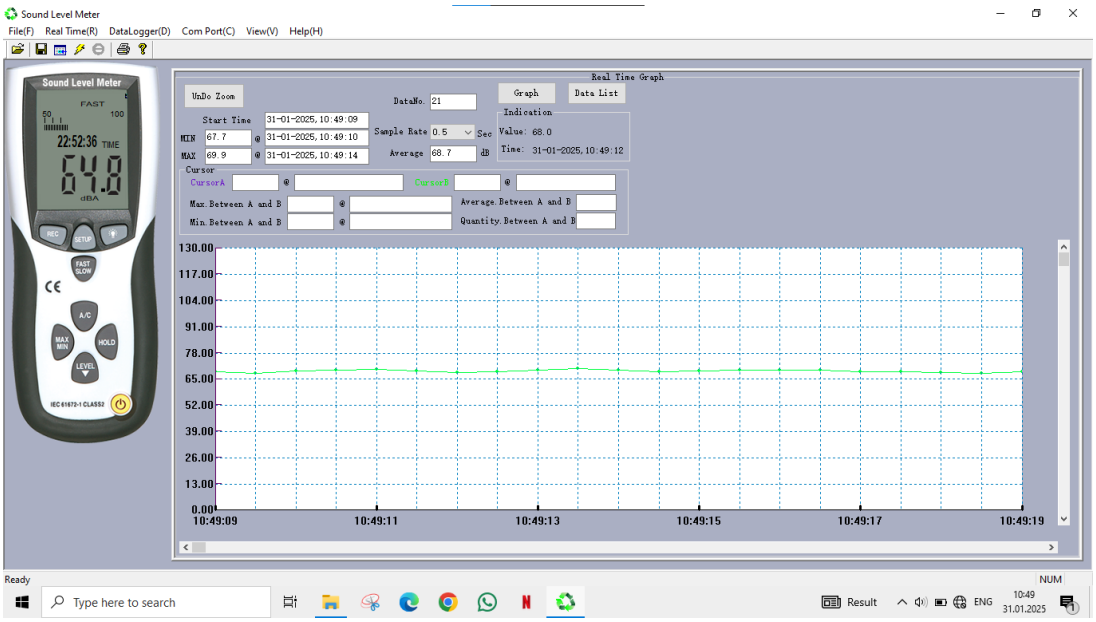


Fig. 9. *Sound Level Meter measurement at 130 km/h in fifth gear after soundproofing*

The results from figure 9, after soundproofing, show a medium decibel level decrease of **3.6 dB** with a minimum decrease in the recorded 10 second period of time of **3.3 dB**.
A decrease of 3.6 dB can be calculated to a percentual decrease of 56% of acoustic power [13]. To the human ear this decrease can be calculated to about 23% reduction of previous sound pressure. Only starting at 3 dB can the human ear percept sound pressure difference and at 10 dB difference the sound pressure sensation is doubled [14].

The decibel reduction results we got for all cases are the following:
Driver: **2.48 db** (medium), **3.6 db** max and **1.2 db** min.
Front passenger: **3.13 db** (medium), **4.7 db** max and **1.6 db** min.
Back passengers: **2.25 db** (medium), **4.9 db** max and **0.8 db** min.
Total medium reduction = **2.6 db**

CONCLUSION

For further reduction of noise level from inside the cars cabin, soundproofing operations can be done on the firewall, wheel arches, hood and rear floor of the spare tire. Besides using soundproofing material we can buy new tires with a better decibel rating, or it can be installed a suspension that lifts the car from the ground a bit more, so road noise made by tires is further away from the driver or the passengers.
The transmission can be modified from 5 gears to one with 6 gears, so lower RPM can be achieved at higher speeds. The exhaust could be replaced with a new one with even better mufflers and more resonating components.
The windows of the car let through a lot of noise, but they are very tough to improve. Having new windows with more layers of glass for better soundproofing would drastically change the comfort.
All these solutions for further improvement can be very expensive and hard to obtain. There is also the issue of the balance between the acoustic comfort reached with how much the work would be worth it. Continuing to soundproof the roof, wheel arches, hood, firewall and rear

floor would be enough for most people, and it would potentially reduce another estimated 3 dB in noise levels

REFERENCES

[1] Vehicle Soundproofing from Knauf Automotive's website: https://knaufautomotive.com/news/car-equipment-and-construction/vehicle-soundproofing/.
[2] Daniel Flor, Danilo Pena, Luan Pena, Vicente A. de Sousa and Jr. 1 and Allan Martins, Characterization of Noise Level Inside a Vehicle under Different Conditions, Sensors 2020, 20, 2471; doi:10.3390/s20092471
[3] Algimantas DANILEVIČIUS, Mykola KARPENKO, Vítězslav KŘIVÁNEK, RESEARCH ON THE NOISE POLLUTION FROM DIFFERENT VEHICLE CATEGORIES IN THE URBAN AREA, DOI: https://doi.org/10.3846/transport.2023.18666
[4] Leupolz, M.; Gauterin, F.,Vehicle Impact on Tire Road Noise and Validation of an Algorithm to Virtually Change Tires. Appl. Sci. 2022, 12, 8810. https://doi.org/10.3390/app12178810
[5] Li, M., Zhou,W., Liu, J.Zhang, X.; Pan, F., Yang, H., Li, M.Luo, D. Vehicle Interior Noise Prediction Based on Elman Neural Network. Appl. Sci. 2021, 11, 8029. https://doi.org/10.3390/app11178029
[6] Julien Cesbron*, Simon Bianchetti, Marie-Agnès Pallas, Adrien Le Bellec, Vincent Gary, Philippe Klein Road surface influence on electric vehicle noise emission at urban speed, Noise Mapp. 2021; 8:217–227, https://doi.org/10.1515/noise-2021-0017
[7] Shawki ABOUEL-SEOUD, Tire and Engine Sources Contribution to Vehicle Interior Noise and Vibration Exposure Levels, ARCHIVES OF ACOUSTICS, Vol. 44, No. 2, pp. 201–214 (2019), DOI: 10.24425/aoa.2019.126366
[8] Mazda 3 Hatchback from 2008 taken from website: https://autoturisme.waa2.ro/detail?id=f675d68e5b0c756b523385dc5ed57d1a&q=mazda%203%20iasi.
[9] The DT-8852 sound level meter made by CEM picture taken from CEM's website:https://www.cem-instruments.com/en/product-id-1294.
[10] STP Bimast Bomb Premium product picture taken from S.C. Autotom Grup S.R.L. website:https://atg.md/ro/catalog/shumoizolyacziya/vibropogloshhayushhie-materialy/bimast-bomb-premium/.
[11] STP Accent 6 product picture taken from SoundHouse's website: https://www.soundhouse.ro/insonorizant/termo-absorbant/insonorizant-auto-stp-accent-6-6mm-375x500mm-foaie.
[12] STP Biplast 10 product picture taken from Noor Tehnik's website: https://noortehnik.ee/en/stp-biplast-10-summutusmaterjal/.
[13] Decibel to percentage calculator provided by lasercalculator through their website: https://www.lasercalculator.com/db-percent-converter/.
[14] "Sound level and auditory perception" blog published byJulie Leduc of Friday, 31 August 2018 on AcoustiTech website: https://www.acoustitech.com/en/blog/detail/sound-level-and-auditory-perception-4129.

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HEALTH AND SAFETY OF EMPLOYEES IN HYBRID WORKING CONDITIONS

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Abstract: The COVID-19 pandemic accelerated the global transition from traditional office work to hybrid and remote models, profoundly reshaping occupational health and safety (OHS). This paper analyzes the challenges and risks associated with hybrid work, with particular emphasis on ergonomic deficiencies, psychosocial stressors, organizational barriers, and regulatory gaps. Improvised home workstations have been shown to increase the prevalence of musculoskeletal disorders (MSDs), while inadequate communication, constant digital connectivity, and lack of social contact contribute to anxiety, burnout, and digital fatigue. Findings also highlight a lack of harmonized OHS standards across countries and organizations, leaving employees vulnerable to unclear responsibilities and insufficient protection. To address these issues, the paper emphasizes the need for integrated strategies that combine ergonomic education, mental health support, transparent organizational policies, and clear legal frameworks. The study concludes that sustainable hybrid work requires the modernization of OHS systems, ensuring inclusivity, resilience, and long-term protection of employee wellbeing.
Key words: *hybrid work, occupational health and safety, ergonomics, digital fatigue, workplace regulation*

INTRODUCTION

The COVID-19 pandemic accelerated the shift from office to remote work, raising questions about sustainability in the post-pandemic era [1]. This transition brought both challenges, such as blurred work-life boundaries, stress, and mental health issues, and opportunities for greater flexibility [2]. Workers reported autonomy and reduced costs, but also anxiety, isolation, and burnout [3, 4, 5, 6].

Organizational policies also changed: studies of tech firms show increased acceptance of flexible work, shifting the psychological contract between employers and employees [7]. Resistance grows when companies restrict work-from-home, while hybrid models differ by size, sector, and culture [1, 8, 9]. Hybrid and remote work have become global norms, linked to access to wider talent pools but also to challenges in digital infrastructure, cybersecurity, and team cohesion [10, 11, 12, 13]. Balancing flexibility with efficiency remains essential [1, 2].

COVID-19 restrictions made telecommuting widespread, changing perceptions of modern work [14]. Digital platforms like Zoom and Teams enabled continuity [13, 15]. Employees now prefer flexibility for better work-life balance, and many would quit rather than return full-time to the office [9,16]. Employers recognize benefits such as lower costs, higher productivity, and resilience [17, 18]. Still, challenges remain: preferences vary by gender, age, and family status, with women often facing heavier workloads and digital fatigue [14, 19]. Flexible work is therefore a structural change in labor organization.

Hybrid models depend on digital tools that reshape communication, agility, and knowledge management [13, 20]. Digitalization fosters flexible structures and faster adaptation to crises [21, 22]. It also enables data-driven decision-making but requires new security and literacy standards [23, 24]. While digitization improves resilience and cohesion, overreliance can cause fatigue and stress. Its success relies on both technology and managerial culture [25, 26].

This paper analyzes challenges and develops recommendations for occupational health and safety (OHS) in hybrid work. Focus is on identifying shortcomings, comparing findings with existing literature, and proposing solutions addressing physical, organizational, and psychosocial risks. The aim is to promote sustainable and inclusive OHS practices supported by technology, improving employee protection, well-being, and resilience in the hybrid work environment.

CHANGE IN THE WORK ENVIRONMENT AND ITS IMPACT ON OHS

Remote work differs from traditional office settings in ergonomics, supervision, and interaction. Home offices are often improvised and linked to higher risks of musculoskeletal disorders (MSD) [15, 27, 28]. Socioeconomic status influences ergonomic conditions, with low-income workers less likely to access proper equipment [29].

Managers face challenges in monitoring performance, coordinating teams, and ensuring security in hybrid settings, while excessive digital surveillance fosters alienation and stress [30, 31, 32]. Unlike office work with direct feedback, remote work often relies on monitoring software, which may undermine trust.

Social interaction is also reduced, informal exchanges that build belonging are missing in remote work, leading to emotional distance, isolation, and weaker team dynamics [29, 33, 34]. These structural differences demand targeted OHS measures, ergonomic education, transparent monitoring, and digital tools that promote cohesion.

Remote work brings technical risks (poor ergonomics, lack of equipment), organizational challenges (supervision, unclear standards), and psychosocial risks (anxiety, isolation, burnout) [2, 4, 35, 36]. Technical problems, such as inadequate workstations, increase MSD risks and require ergonomic guidelines and workspace assessments [27, 37].

Organizationally, digitization enables flexibility but is ineffective without supportive culture; hierarchical firms showed more productivity decline [21, 22, 38]. Recommendations include clear policies, trust-based monitoring, and training managers for virtual teams [30].

Psychosocial risks include emotional exhaustion and blurred work-life boundaries [3, 4]. Mitigation strategies involve mental health programs, digital break rules, and social support [36, 39, 40]. Integrated approaches, such is combining ergonomics, digital infrastructure, and psychological support, are necessary for sustainable OHS [41, 42].

Remote work intensified isolation, digital fatigue, and blurred boundaries. Isolation weakens psychological safety and reduces initiative [43, 44, 45]. Digital fatigue stems from constant camera use and self-monitoring, causing cognitive overload [46, 47, 48]. Constant connectivity fosters pressure to remain available, disrupting rest and relationships [49, 50, 51].

These stressors require policies promoting digital hygiene, time boundaries, detox strategies, and virtual psychological safety to protect employees' mental health.

ANALYSIS OF CHALLENGES AND RISKS IN REMOTE WORK

Improvised home offices increase risks of MSDs [27]. Studies show high prevalence of neck and back pain among employees without ergonomic setups [35, 52, 53]. Poor equipment and lighting especially affect lower-income workers. Ergonomic deficiencies reduce efficiency, increase sick leave, and are a public health issue [54]. Policies should set minimum technical standards, provide training, and ensure regular workplace checks.

Telework often involves kitchen chairs, beds, poor lighting and lack of ergonomic standards, increasing MSDs and psychosocial stress [55, 56]. Reviews confirm higher incidence of pain in hybrid workers compared to office-based ones [57, 58]. Inadequate ergonomics also links to digital fatigue and stress due to blurred home–work boundaries [32, 33]. Solutions include systemic standards, equipment provision, training, and institutional support for adapting home workplaces.

Lack of direct supervision reduces motivation, increases stress, and fosters burnout [59]. Poor communication and feedback mechanisms worsen isolation, while supportive managers mitigate these effects. Constant self-assessment without guidance leads to feelings of

underperformance. Systemic solutions involve structured communication, mentoring, and feedback programs.

Remote work intensifies burnout, loneliness, and overload. Employees report emotional exhaustion due to constant availability and inadequate support [59]. Lack of informal social contact reduces belonging and cooperation [60]. Isolation further reduces motivation and increases fatigue. Organizations should implement group support, contact sessions, and wellbeing programs to maintain engagement.

Remote and Work from anywhere (WFA) models increase risks of cyber threats, privacy violations, and digital overload [30]. Use of personal devices without protection, lack of training, and decentralized infrastructure create vulnerabilities. Constant connectivity raises stress and dependence, making cybersecurity part of OHS. Cross-sector policies, training, and clear digital behavior guidelines are necessary.

The International Labor Organisation (ILO) highlights risks and opportunities of teleworking, stressing ergonomics, mental health, and the need for employer support [11]. A practical guide and a checklist for small and medium-sized enterprises (SMEs) set out clear recommendations on working hours, equipment, and communication. Both treat telework as a long-term reality and call for strategies that make remote work safe, healthy, and inclusive, with explicit attention to mental health and to safeguarding the right to disconnect. Empirical evidence links hybrid work to heightened psychosocial and ergonomic risks. IT professionals report elevated anxiety and burnout [30], while staff in education and administration experience exhaustion driven by digital fatigue [59]. Inadequate home-office ergonomics correlate with MSDs and increased stress [27, 55]. Reviews also identify loneliness as a prominent concern [60]. Privacy-respecting monitoring of workload and well-being indicators, structured self-assessments, and regular one-to-one/team check-ins are associated with better well-being and engagement.

ASSESSMENT OF THE EXISTING SITUATION AND THE NEED FOR INNOVATION

Despite the spread of remote work, most countries lack adequate legislation. Only 9 of 27 EU countries have a right-to-disconnect law [53]. Corporate policies vary, some require office days, others none [7]. The absence of regulation leaves employees exposed to unclear rules and risks for balance, health, and safety. National laws should define minimum rights, disconnection policies, and office presence rules.

OHS regulations are clear for offices but vague for home settings [53]. Employers cannot fully control private workspaces, creating liability gaps. There is the need for clearer national policies defining employer and employee responsibilities for both physical and psychosocial wellbeing. Minimum ergonomic standards, availability rules, and emotional support should be formally regulated.

Although isolation, stress, and burnout are well documented, most organizations neglect them in OHS policies. Meta-analyses show high rates of anxiety, depression, and fatigue among teleworkers. Recommended measures include integrating ISO 45003, adopting disconnection policies, regular wellbeing surveys, and manager training.

Clear rules on availability, core working hours, and flextime balance personal and professional needs. Educational programs on digital tools, virtual team leadership, and mental health improve safety and reduce stress. Transparent communication strengthens trust and engagement in distributed teams.

Current OHS standards lag behind digital work realities. Ropponen [53] calls for longitudinal studies and regulatory models tracking work hours and digital connectivity. Comprehensive frameworks for home offices, mental health, and disconnection are needed. Wearables and connected-worker platforms can monitor stress, ergonomics, and health in real time. Future norms should integrate digital infrastructure, mental health protection, and fair application of emerging technologies.

CONCLUSION

Hybrid and remote work have become permanent features of the modern labor market, offering flexibility and efficiency but also posing new and complex risks for OHS. This paper demonstrated that inadequate ergonomic conditions, blurred work-life boundaries, social isolation, and the absence of clear supervisory structures can significantly undermine employee wellbeing. Moreover, insufficient regulatory frameworks and fragmented organizational policies leave critical gaps in protecting workers from physical, organizational, and psychosocial hazards.

Addressing these challenges requires a holistic and proactive approach. Employers should implement minimum ergonomic standards, training programs for digital literacy and virtual leadership, and policies that guarantee the right to disconnect. Equally important are initiatives to promote mental health, strengthen social cohesion in distributed teams, and foster transparent communication and trust. At the policy level, governments and institutions must harmonize OHS regulations with the realities of hybrid work, ensuring shared responsibility between employers and employees.

Ultimately, sustainable hybrid work environments depend not only on digital infrastructure but also on supportive managerial cultures and inclusive OHS strategies. By integrating ergonomic, psychological, organizational, and regulatory measures, hybrid work can evolve into a resilient and healthy model that safeguards both productivity and employee wellbeing.

Future work should include longitudinal, multi-sector studies that combine validated psychosocial and ergonomic scales with privacy-preserving digital/wearable data to chart risk trajectories in hybrid and remote settings. In parallel, randomized or quasi-experimental evaluations of organization-level interventions (e.g., right-to-disconnect policies, virtual-leadership training, ergonomic micro-grants), coupled with development of a Hybrid OHS Wellbeing Index and cost–benefit analyses, are needed to guide regulation and SME practice.

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REFERENCES

[1] Smite, D., Moe, N. B., Baldassarre, M. T., Calefato, F., Travassos, G. H., Floryan, M., Kalinowski, M., Mendez, D., Pereira, G. B., Storey, M. A., Prikladnicki, R.: Who "controls" where work shall be done? State-of-practice in post-pandemic remote work regulation, 2025.

[2] Giorgi, G., Lecca, L. I., Alessio, F., Finstad, G. L., Bondanini, G., Lulli, L. G., Arcangeli, G., Mucci, N.: COVID-19-Related Mental Health Effects in the Workplace: A narrative Review, International Journal of Environmental Research and Public Health, 17(21), 7857, 2020.

[3] Kniffin, K. M., Narayanan, J., Anseel, F., Antonakis, J., Ashford, S. P., Bakker, A. B., Vugt, M. V.: COVID-19 and the workplace: Implications, issues, and insights for future research and action, American Psychologist, 76(1), 63–77, 2021.

[4] Xiao, Y., Becerik-Gerber, B., Gale, L., Shawn, C. R.: Impacts of Working From Home During COVID-19 Pandemic on Physical and Mental Well-Being of Office Workstation Users, Journal of Occupational and Environmental Medicine, 63(3), 181-190, 2021.
[5] Carnevale, J. B., Hatak, I.: Employee adjustment and well-being in the era of COVID-19: Implications for human resource management, Journal of Business Research, 116, 183–187, 2020.
[6] Galanti, T., Guidetti, G., Mazzei, E., Zappalà, S., Toscano, F.: Work from home during the COVID-19 outbreak: The impact on employees' remote work productivity, engagement, and stress, Journal of Occupational and Environmental Medicine, 63(7), e426–e432, 2021.
[7] Smite, D., Moe, N. B., Hildrum, J., Hierta, J. G., Mendez, D.: Work from home is here to stay: Call for flexibility in post pandemic work policies, 2022.
[8] Barrero, J. M., Bloom, N., Davis, S. J.: Why working from home will stick? National Bureau of Economic Research Working Paper No. 28731, 2021.
[9] Bloom, N., Liang, J., Roberts, J., Ying, Z. J.: Does working from home work? Evidence from a Chinese experiment, Quarterly Journal of Economics, 130(1), 165–218, 2015.
[10] Eurofound: Living, working and COVID-19, Research Report, 2020.
[11] International Labour Organization: Teleworking during the COVID 19 pandemic and beyond: A practical guide,2020.
[12] Vyas, L.: "New normal" at work in a post-COVID world: work–life balance and labor markets, Policy and Society, 41(1), 155-167, 2022.
[13] Waizenegger, L., McKenna, B., Cai, W., Bendz, T.: An affordance perspective of team collaboration and enforced working from home during COVID-19, European Journal of Information Systems, 29(4), 429–442, 2020.
[14] Waldrep, C. E., Fritz, M., Glass, J.: Preferences for remote and hybrid work: Evidence from the COVID-19 pandemic, Social Sciences, 13(6), 303, 2024.
[15] Liu, H., Li, X., Wang, S.: A bibliometric analysis of 30 years of platform research: Developing the research agenda for platforms, the associated technologies and social impacts, Technological Forecasting and Social Change, 169, 120827, 2021.
[16] Ipsen, C., van Veldhoven, M., Kirchner, K., Hansen, J. P.: Six key advantages and disadvantages of working from home in Europe during COVID-19, International Journal of Environmental Research and Public Health, 18(4), 1826, 2021.
[17] Allen, T. D., Golden, T. D., Shockley, K. M.: How effective is telecommuting? Assessing the status of our scientific findings, Psychological Science in the Public Interest, 16(2), 40–68, 2015.
[18] IntechOpen, Flexible Work Options in the COVID-19 Period, Available at Flexible Work Options in the COVID-19 Period | IntechOpen.
[19] Spurk, D., Straub, C.: Flexible employment relationships and careers in times of the COVID-19 pandemic, Journal of Vocational Behavior, 119, 103435, 2020.
[20] Nakash, M., Bouhnik, D.: The effects of COVID-19 on information management in remote and hybrid work environments, Journal of the Association for Information Science and Technology, 74(9), 1067–1080, 2023.
[21] Ciampi, F., Faraoni, M., Ballerini, J., Meli, F.: The co-evolutionary relationship between digitalization and organizational agility: Ongoing debates, theoretical developments and future research perspectives, Technological Forecasting and Social Change, 176, 121383, 2022.

[22] Teece, D., Peteraf, M., Leih, S.: Dynamic Capabilities and Organizational Agility: Risk, Uncertainty, and Strategy in the Innovation Economy, California Management Review, 58(4), 13-35, 2016.
[23] Sebastian, I. M., Ross, J. W., Beath, C. M., Mocker, M., Moloney, K. G., Fonstad, N. O.: How big old companies navigate digital transformation, MIS Quarterly Executive, 16(3), 197–213, 2017.
[24] Bharadwaj, A., El Sawy, O. A., Pavlou, P. A., Venkatraman, N.: Digital business strategy: Toward a next generation of insights, MIS Quarterly, 37(2), 471–482, 2013.
[25] Leonardi, P. M.: COVID-19 and the new technologies of organizing: Digital exhaust, digital footprints, and artificial intelligence in the wake of remote work, Journal of Management Studies, 58(1), 249–253, 2020.
[26] Majchrzak, A., Markus, M. L., Wareham, J.: Designing for digital transformation: Lessons for information systems research from the study of ICT and societal challenges, MIS Quarterly, 40(2), 267–277, 2016.
[27] Milaković, M., Koren, H., Bradvica-Kelava, K., Bubaš, M., Nakić, J., Jeličić, P., Bucić, L., Bekavac, B., Čvrljak, J., Capak, M.: Telework-related risk factors for musculoskeletal disorders: A review, Frontiers in Public Health, 11, 1155745, 2023.
[28] Moretti, A., Menna, F., Aulicino, M., Paoletta, M., Liguori, S., Iolascon, G.: Characterization of home working population during COVID-19 emergency: A cross-sectional analysis, International Journal of Environmental Research and Public Health, 17(17), 6284, 2020.
[29] El Kadri Filho, F., de Lucca, S. R.: Telework conditions, ergonomic and psychosocial risks, and musculoskeletal problems in the COVID 19 pandemic, Journal of Occupational and Environmental Medicine, 64(12), e811–e817, 2022a.
[30] Blaszczyk, M., Popović, M., Zajdel, K., Zajdel, R.: Implications of the COVID-19 pandemic on the organization of remote work in IT companies: The managers' perspective, Sustainability, 15(15), 12049, 2023.
[31] De Macêdo, T. A. M., Cabral, E. L. S., Silva Castro, W. R., de Souza Júnior, C. C., da Costa Junior, J. F., Pedrosa, F. M., da Silva, A. B., de Medeiros, V. R. F., de Souza, R. P., Cabral, M. A. L., Másculo, F. S.: Ergonomics and telework: A systematic review, Work, 66(4), 777–788, 2020.
[32] Schneckenberg, D., Benítez, J., Klos, C., Velamuri, V. K., Spieth, P.: Value creation and appropriation of software vendors: A digital innovation model for cloud computing, Information & Management, 58(4), 103463, 2021.
[33] Oakman, J., Kinsman, N., Stuckey, R., Graham, M., Weale, V.: A rapid review of mental and physical health effects of working at home: How do we optimize health? BMC Public Health, 20, 1825, 2020.
[34] Tavares, A. I.:Telework and health effects review, International Journal of Healthcare, 3(2), 30–36, 2017.
[35] Ahmed, S., Qamar, F., Soomro, S. A.: Ergonomic work from home and occupational health problems amid COVID-19, Human Systems Management, 41(1), 1–17, 2022.
[36] Koren, H., Milaković, M., Bubaš, M., Bekavac, P., Bekavac, B., Bucić, L., Čvrljak, J., Capak, M., Jeličić, P.: Psychosocial risks emerged from COVID-19 pandemic and workers' mental health, Frontiers in Psychology, 14, 1148634, 2023.
[37] Ralph, P., Baltes, S., Adisaputri, G., Torkar, R., Kovalenko, V., Kalinowski, M., Alkadhi, R.: Pandemic programming: How COVID-19 affects software developers and how their organizations can help, 2020.

[38] Verhoef, P. C., Broekhuizen, T., Bart, Y., Bhattacharya, A., Dong, J. Q., Fabian, N., Haenlein, M.: Digital transformation: A multidisciplinary reflection and research agenda, Journal of Business Research, 122, 889–901, 2021.
[39] Fostervold, K. I., Ulleberg, P., Nilsen, O. V., Halberg, A. M.: The hidden costs of working from home: examining loneliness, role overload, and the role of social support during and beyond the COVID-19 lockdown, Frontiers in Organizational Psychology, 2, 1380051, 2024.
[40] Karabinski, T., Haun, V. C., Nübold, A., Wendsche, J., Wegge, J.: Interventions for improving psychological detachment from work: A meta-analysis, Journal of Occupational Health Psychology, 26(3), 224–242, 2021.
[41] Stein, M., Schümann, M., Teetzen, F., Gregersen, S., Begemann, V., Vincent-Höper, S.: Supportive leadership training effects on employee social and hedonic well-being: A cluster randomized controlled trial, Journal of Occupational Health Psychology, 26(6), 599–612, 2021.
[42] Liu, E. H., Chambers, C. R., Moore, C.: Fifty years of research on leader communication: What we know and where we are going, The Leadership Quarterly, 34(6), 101734, 2023.
[43] Tkalich, A., Smite, D., Andersen, N. H., Moe, N. B.: What happens to psychological safety when going remote, 2022.
[44] Edmondson, A.: Psychological safety and learning behavior in work teams, Administrative Science Quarterly, 44(2), 350–383, 1999.
[45] Carmeli, A., Brueller, D., Dutton, J. E.: Learning behaviours in the workplace: The role of high-quality interpersonal relationships and psychological safety, Systems Research and Behavioral Science, 26(1), 81–98, 2008.
[46] Raake, A., Fiedler, M., Schoenenberg, K., De Moor, K., Döring, N.: Technological factors influencing videoconferencing and Zoom fatigue, 2022.
[47] Bailenson, J. N.: Nonverbal overload: A theoretical argument for the causes of Zoom fatigue. Technology, Mind, and Behavior, 2(1), 2021.
[48] Wiederhold, B. K.: Connecting through technology during the coronavirus disease 2019 pandemic: Avoiding "Zoom fatigue", Cyberpsychology, Behavior, and Social Networking, 23(7), 437–438, 2020.
[49] Mirbabaie, M., Marx, J., Braun, L. M., Stieglitz, S.: Digital Detox -- Mitigating Digital Overuse in Times of Remote Work and Social Isolation, Australasian Conference on Information Systems, Wellington, New Zealand, 2020.
[50] Derks, D., van Mierlo, H., Schmitz, E. B.: A diary study on work-related smartphone use, psychological detachment and exhaustion: Examining the role of the perceived segmentation norm, Journal of Occupational Health Psychology, 19(1), 74–84, 2014.
[51] Reinecke, L., Aufenanger, S., Beutel, M. E., Dreier, M., Quiring, O., Stark, B., Wölfling, K., Müller, K. W.: Digital stress over the life span: The effects of communication load and internet multitasking on perceived stress and psychological health impairments in a German probability sample, Media Psychology, 20(1), 90–115, 2017.
[52] Narainsamy, N., Akpa-Inyang, F. F., Onwubu, S. C., Govender, N., Pillay, J. D.: Ergonomic Challenges and Musculoskeletal Pain During Remote Working: A Study of Academic Staff at a Selected University in South Africa During the COVID-19 Pandemic, International Journal of Environmental Research and Public Health, 22(1):79, 39857531, 2025.
[53] Ropponen, A. (2025). Remote work – the new normal needs more research, Scandinavian Journal of Work, Environment & Health, 51(2), 53-57, 2025.

[54] Bräutigam, L. R.: The Home Office: Achieving Productivity, Well-Being and Ergonomics, In: Knappertsbusch, I., Wisskirchen, G. (eds) The Future of Work. Springer, Wiesbaden, 2024.
[55] El Kadri Filho, F., de Lucca, S. R.: Telework during the COVID-19 pandemic: Ergonomic and psychosocial risks among Brazilian labor justice workers, Work, 71(2), 395–405, 2022b.
[56] Gerding, T., Syck, M., Daniel, D., Naylor, J., Kotowski, S. E., Gillespie, G. L., Freeman, A. M., Huston, T. R. Davis, K. G.: An assessment of ergonomic issues in the home offices of university employees sent home due to the COVID-19 pandemic, Work, 68(4), 981–992, 2021.
[57] Alencar, M. do C. B., da Silva, N. R., Serranheira, F.: Musculoskeletal pain and risk factors in office workers versus teleworkers: A systematic review, Work, 80(3), 974–997, 2025.
[58] Cruz-Ausejo, L., Copez-Lonzoy, A., Vilela-Estrada, A. L., Valverde, J. J., Bohórquez, M., Moscoso-Porras, M.: Can working at home be a hazard? Ergonomic factors associated with musculoskeletal disorders among teleworkers during the COVID-19 pandemic: A scoping review, International Journal of Occupational Safety and Ergonomics, 29(4), 1335–1344, 2022.
[59] Costin, A., Alina, R., Balica, R. Ș.: Remote work burnout, professional job stress, and employee emotional exhaustion during the COVID-19 pandemic, Frontiers in Psychology, 14, 1193854, 2023.
[60] Wu, X.: The Impact of Remote Work on Workplace Loneliness During and after COVID-19: A Literature Review, Communications in Humanities Research, 39(1), 251–258, 2024.

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EVALUATION OF NOISE EXPOSURE FROM PRINTING MACHINES IN A DIGITAL PRINTING LABORATORY

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Abstract: This paper presents an evaluation of noise exposure in a digital printing laboratory equipped with seven machines used for production and teaching. Equivalent continuous sound levels (Leq) ranged from 63.9 to 80.5 dB(A), all below the occupational threshold of 85 dB(A). Additional 1/3 octave band analyses were carried out for three representative machines. The spectra revealed dominant mid-frequency components (500–1000 Hz), overlapping with the range critical for speech, which may interfere with communication. Although the risk of hearing impairment is minimal, prolonged exposure could lead to fatigue and reduced concentration. Preventive measures are advised to improve acoustic conditions.
Key words: occupational noise, digital printing equipment, frequency spectra, communication interference

INTRODUCTION

The rapid expansion of digital printing technologies has significantly changed the printing industry. Digital printing equipment such as laser printers and photocopiers is now widely used not only for office documents, but also for industrial applications including ceramics, porcelain, glass decoration [1], and textile production [2]. These processes, while technologically advanced and flexible, also introduce new environmental and occupational challenges.
Noise is one of the most common physical stressors in printing facilities. It is generally defined as undesirable sound that negatively affects human health and wellbeing [3]. Prolonged exposure to elevated noise levels has been associated not only with hearing impairment but also with a range of non-auditory effects, including annoyance, concentration problems, fatigue, cardiovascular diseases, and interference with speech communication [4, 5]. International guidelines usually set occupational limits for noise between 85 and 90 dB(A), but even long-term exposure above 75 dB(A) may be considered harmful [6]. The human ear is most sensitive to frequencies between 400 and 4000 Hz, where excessive noise particularly interferes with speech comprehension.
Considering the importance of safe and effective work and study environments, this study aimed to evaluate noise levels generated by seven different printing machines used in a digital printing laboratory. Special attention was given to the comparison of measured values with permissible limits, and to the analysis of noise frequency spectra. .

MATERIAL AND METHODS

The study was conducted in the digital printing laboratory of the Department of Graphic Engineering and Design, Faculty of Technical Sciences, University of Novi Sad, Serbia. The laboratory is regularly used for both production and educational purposes. Two employees worked daily in the facility, with students attending practice sessions during the monitoring period.

The following seven machines were included in the study:
1. Single-color digital printing machine (Xerox D95A)
2. Four-color digital printing machine (Xerox DocuColor 252)

3. Cutting machine (Perfecta 76 HTVC)
4. Perfect binder (Horizon BQ-270)
5. Paper collating machine (Horizon VAC-100)
6. Screen printing machine (S550)
7. Saddle stitch binding machine (Hohner Exact)

The laboratory layout and machine arrangement allowed measurements to be taken next to each machine while others were not in operation.
To place the measurements into context, Table 1 summarizes adverse health effects related to occupational noise exposure, documented in epidemiological studies [7]. These reference values provide a framework for interpreting the results obtained in this study.

Table 1. *Examples of long-term effects related to noise exposure. Noise levels are given as L_{Aeq} levels measured over a period of time (eight hours).*

Effect	Exposure type	L_{Aeq} [dB(A)]	Location
Hearing impairment	Occupational	75	Indoors
Hypertension	Occupational	<85	Indoors
Annoyance	Occupational	<85 (Industry); <55 (Office)	Indoors

Noise measurements

Sound pressure levels (SPL) were measured using a TES-1358A Sound Level Meter (SLM) with RS-232 interface. Measurements were carried out over three working weeks. For each machine, five sets of measurements (n = 5), each of 15 minutes duration, were performed in standard operating mode at different times of the working week. The equivalent continuous sound level (L_{Aeq}) in dB(A) was recorded. Measurements were conducted according to EU and Serbian regulations on occupational noise exposure [8, 9].

Frequency analysis

For the saddle stitch binding machine, the cutting machine, and the single-color digital printing machine, additional analysis was carried out in 1/3 octave bands. The obtained spectra were compared with the interpolated NR-35 curve, an internationally recognized standard for acceptable indoor noise levels in relation to hearing protection, annoyance, and speech communication [10]. In addition, since the laboratory is used for teaching activities, the threshold level of 40 dB prescribed for classrooms and laboratories by the national regulation on environmental noise was also considered.

RESULTS AND DISCUSSION

Table 2 presents the mean noise levels with standard deviations for all machines included in the study. All measured L_{Aeq} values were below the occupational threshold of 85 dB(A). The highest level was recorded for the saddle stitch binding machine (80.5 dB(A)), followed by the cutting machine (74.9 dB(A)) and the perfect binder (74.2 dB(A)). The lowest average levels were observed for the four-color digital machine (63.9 dB(A)).

Table 2. *Average noise levels (L_{Aeq}) for different types of printing machines*

Printing machine	L_{Aeq} [dB(A)] (±SD)
Single-color digital machine	66.7 (±2.35)
Four-color digital machine	63.9 (±2.45)
Cutting machine	74.9 (±4.10)
Perfect binder	74.2 (±1.59)
Paper collating machine	72.2 (±2.12)
Screen printing machine	72.8 (±1.90)
Saddle stitch binding machine	80.5 (±3.90)

This paper examines noise effects from two perspectives: the potential impact on machine operators and on students attending practice sessions. As shown in Table 2, equivalent noise levels for all machines were well below 85 dB(A), while daily operating times typically did not exceed several hours. Based on these findings, it can be concluded that neither employees nor students are exposed to the risk of hearing impairment. Also, considering that the L_{Aeq} values for digital printing machines are 63.9 and 66.7 dB(A), and < 75 dB(A) for other machines, there is no risk of manifestation of potential non-auditory effects of noise.
Since the mean SPL values for all machines exceeded the 40 dB(A) limit prescribed for laboratories and classrooms [8, 9], additional measurements were carried out in 1/3 octave bands. Frequency spectra were obtained for all machines, while detailed graphical presentations are shown only for the cutting machine, the single-color digital printing machine, and the saddle stitch binding machine (Figures 1–3). The cutting machine produced the highest noise levels in the 500–2000 Hz range, with a peak at 800 Hz. A similar distribution was observed for the single-color digital machine, with a maximum at 500 Hz. IN contrast, the saddle stitch binding machine exhibited elevated levels across the spectrum, with distinct peaks at 630 and 1250 Hz and further increases up to 8000 Hz.

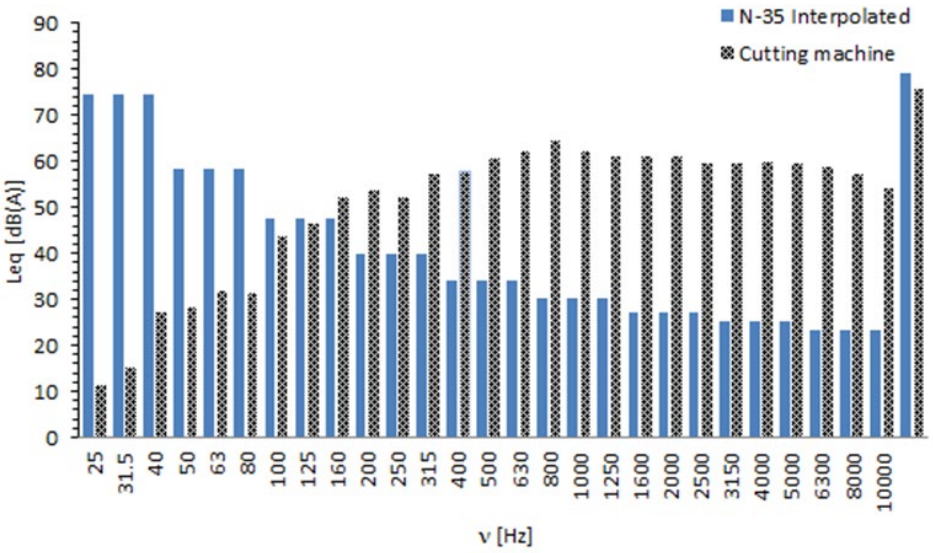


Fig. 1. *Noise spectrum of the cutting machine*

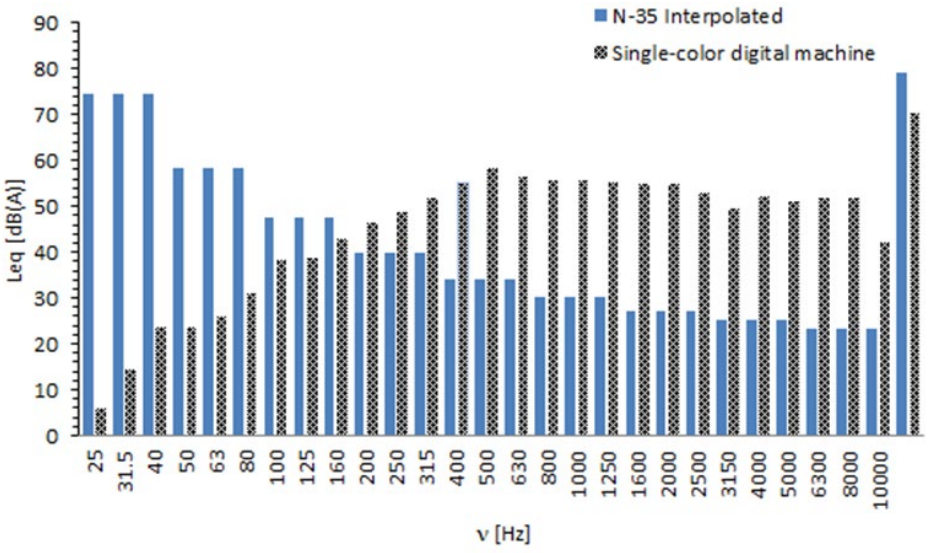


Fig. 2. *Noise spectrum of the single-color digital printing machine*

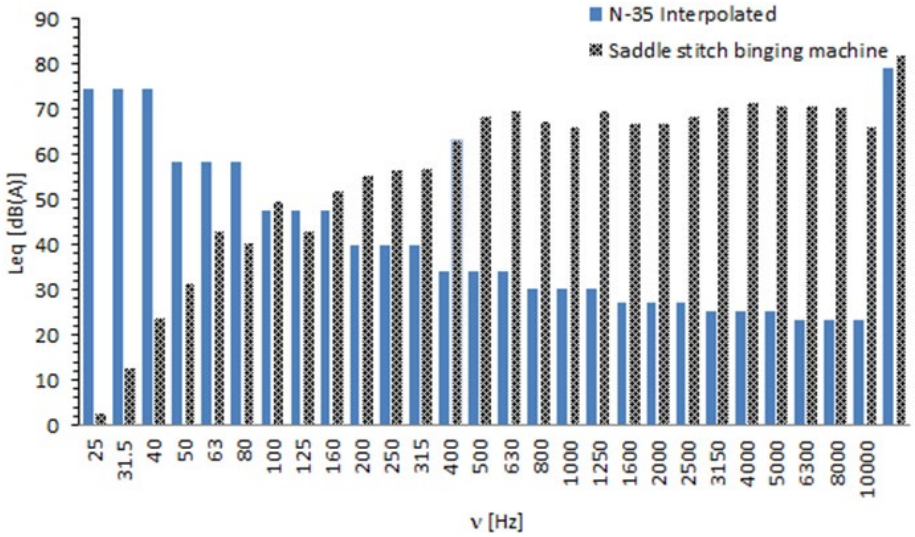


Fig. 3. *Noise spectrum of the saddle stitch binding machine*

Comparison with the NR-35 curve confirmed that all machines exceeded 35 dB(A) in the frequency range critical for human speech perception (300–700 Hz). This indicates potential interference with communication in the laboratory. The saddle stitch binding machine produced levels approaching the maximum allowed L_{Aeq}. Although immediate risk of hearing loss is unlikely, prolonged exposure may lead to fatigue, reduced concentration, and speech interference.

CONCLUSION

Noise as a physical stressor was present in the digital printing laboratory for all seven investigated machines, with measured L_{Aeq} values ranging from 63.9 dB(A) for the four-color digital printing machine to 80.5 dB(A) for the saddle stitch binding machine. Although all values were below the occupational threshold of 85 dB(A), several machines, particularly the cutting machine and the perfect binder, produced levels close to or above 75 dB(A), which may still be associated with non-auditory health effects such as fatigue and annoyance. Frequency analysis in 1/3 octave bands was performed for three representative machines. The spectra were dominated by mid-frequency noise components, with peaks around 500, 630, 800, and 1250 Hz. Since the critical frequency range for human speech is between 300 and 700 Hz, these noise levels indicate potential interference with communication during work or teaching activities in the laboratory. Overall, the results suggest that although the risk of permanent hearing damage is low, noise may affect concentration and speech intelligibility. Preventive measures such as minimizing simultaneous operation of multiple machines, occasional switching-off during classes, and optimizing room arrangement could contribute to improved acoustic conditions in the laboratory.

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REFERENCES

[1] Lee, J.-H., Kweon J.-W., Cho W.-S., Kim J.-H., Hwang K.-T., Hwang H.-J., Han K.-S., Formulation and characterization of black ceramic ink for a digital ink-jet printing, Ceramics International, Vol, 44, pp 14151-14157, 2018.
[2] Ye, W., Lin, J., Borrego, R., Chen, D., Sotto, A., Luis, P., Liu, M., Zhao, S., Tang, C. Y., Van der Bruggen, B., Advanced desalination of dye/NaCl mixtures by a loose nanofiltration membrane for digital ink-jet printing, Separation and Purification Technology, Vol. 197,pp. 27-35, 2018.
[3] Münzel, T., Gori, T., Babisch, W., Basner, M., Cardiovascular effects of environmental noise exposure, European Heart Journal, Vol. 35, pp. 829-836, 2014.
[4] Basner, M., Babisch, W., Davis, A., Brink M., Clark, C., Janssen, S., Stansfeld, S., Auditory and non-auditory effects of noise on health, Lancet, Vol. 383 , pp. 1325-1332 2014.
[5] Lafferty, J.S., Public Health Madison and Dane County, Potential health effects of noise exposure, 2018.
[6] Mokhtar, M., Kamaruddin, S., Khan, Z.A., Mallicka, Z., Study on the effects of noise on industrial workers in Malaysia, Jurnal Teknologi, Vol. 46, pp. 17-30, 2007.
[7] Passchier-Vermeer, W., Passchier, W.F., Noise exposure and public health, Environmental Health Perspectives, Vol. 108, pp. 123-131, 2000.
[8] Directive 2003/10/EC of the European Parliament and of the Council of 6 February 2003 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (noise) (Seventeenth individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC).
[9] Official Gazette of the Republic of Serbia No. 75/10, Regulation on noise indicators, limit values, noise indicators assessment methods, annoyance and harmful effects of environmental noise, 2010 (in Serbian).
[10] ISO 1996-1, International Organization for Standardization, Acoustics - Description, measurement and assessment of environmental noise. Part 1: Basis quantities and assessment procedures, International Organization for Standardization, Geneva, Switzerland, 2003.

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MOBILE APPLICATIONS FOR A HEALTHY AND BALANCED DIET: A REVIEW AND COMPARISON

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Abstract: In today's digital society, mobile applications are increasingly becoming valuable tools for supporting a healthy lifestyle. A special segment consists of applications designed to promote healthy eating habits, meal planning, diet tracking, and calorie intake control. This paper analyzes and compares the most popular applications for healthy nutrition. The conclusion of this study is that, with sufficient motivation and education, digital tools can positively influence changes in eating habits but cannot fully replace professional nutritional support.
Key words: digital nutrition, mobile applications for nutrition, nutrition science

INTRODUCTION

The presence of obesity has increased dramatically in modern society and is an independent factor that induces the numerous cardiovascular diseases – the main causes of death worldwide [1,2]. In 2022, 43% of adults were classified as overweight [3]. A fast-paced lifestyle, stress, and the widespread availability of high-calorie foods have significantly contributed to the development of unhealthy eating habits, resulting in a growing number of individuals affected by obesity, which is a risk factor for type 2 diabetes, and other metabolic and cardiovascular disorders [4].
As a response to previous challenges, a significant number of people turn to digital solutions to monitor, analyze and improve their dietary behavior. Mobile nutrition applications present important and popular tools for achieving, analyzing and maintaining a healthy and balanced diet [5]. These apps enable users to monitor progress in real time, track their calories and nutrient intake, receive personalized recommendations and plan meals. Designed to be user-friendly and accessible via smartphones, they often include additional features such as physical activity tracking, weight monitoring, and hydration reminders, offering a comprehensive approach to health management.
There is a wide spectrum of nutrition applications that vary in terms of interface design, functionality, target demographics and pricing models. Over the past decade, the popularity and relevance of such applications have grown continuously, accordingly with increased public awareness of disease prevention through proper nutrition. On the other hand, their widespread availability opens new questions about their effectiveness, suitability for different types of users, accuracy and improvement.
This paper will review and provide a comparative analysis of several mobile applications designed to support healthy and balanced eating. The focus in our consideration will be on key features and the measure to which mobile apps help users achieve their dietary goals.

METABOLIC SYNDROME

Metabolic syndrome, also known as syndrome X, is associated with an increased risk of several chronic diseases, including type 2 diabetes, atherosclerotic cardiovascular disease,

chronic kidney disease and cancers, and presents basic role in early prevention [4]. The International Diabetes Federation (IDF) made the following metabolic syndrome definition [9]:

1. Central obesity (defined as increased waist circumference based on ethnicity-specific values; measurement of waist circumference is not required if the body mass index is equal to or greater than 30 kg/m^2),
2. and any two of the following four parameters:
   a) Increased blood pressure (systolic pressure is equal to or greater than 130 mmHg, or diastolic pressure is equal to or greater than 85 mmHg),
   b) Decreased high-density lipoprotein (HDL) cholesterol (less than 1.29 mmol/L in females and less than 1.03 mmol/L in males),
   c) Increased triglycerides (equal to or greater than 1.7 mmol/L),
   d) Increased fasting plasma glucose (equal to or greater than 5.6 mmol/L).

HEALTHY AND BALANCED DIET

According to leading health organizations such as the World Health Organization (WHO) [6], the European Food Safety Authority (EFSA) [7], and the United States Department of Agriculture (USDA) together with the United States Department of Health and Human Services (HHS) [7], a healthy and balanced diet should include a variety of foods that provide essential nutrients in appropriate proportions. Based on this, key recommendations include:
- Adequate intake of proteins, carbohydrates, and fats in appropriate ratios,
- Sufficient consumption of vegetables and fruits (as sources of vitamins, minerals, and dietary fiber),
- Limited intake of saturated fats and free sugars,
- Moderate salt consumption,
- Proper hydration, primarily through water.

A healthy and balanced diet, based on these principles, improves physical and mental performance, promotes overall health, and reduces the risk of numerous chronic diseases.

OVERVIEW OF MOBILE APPS

MyFitnessPal

MyFitnessPal, launched in 2005 by Mike Lee, has become a widely used nutrition and fitness tracking app, serving as a daily companion for millions of users worldwide. This app allows users to log food intake through barcode scanning, search, or by creating their own custom recipes, monitor carbohydrates, proteins and fats, track calories, as well as physical activity and weight changes [10]. MyFitnessPal has a big food database with millions of food entries. The layout of the MyFitnessPal app is shown in Fig. 1.

YAZIO

Mobile app YAZIO has been created in 2014 and quickly gained popularity among users seeking a more structured approach to healthy eating and weight management. As MyFitnessPal app, YAZIO provides users to log their food intake through barcode scanning, manual entry, or by adding custom meals and recipes. Providing detailed nutritional information, YAZIO enables users to monitor calorie intake and distribution of proteins, carbohydrates and fats, tracking physical activity and weight changes [10]. However, the key features of YAZIO include personalized meal plans and intermittent fasting options, which are particularly appealing to users aiming for specific health or fitness goals. While MyFitnessPal boasts a significantly large food database, YAZIO offers carefully selected nutritional content and recipes adapted to dietary preferences such as vegetarian, vegan or low-carb. In addition,

YAZIO provides a modern and intuitive interface, with user-friendly navigation and clean design.

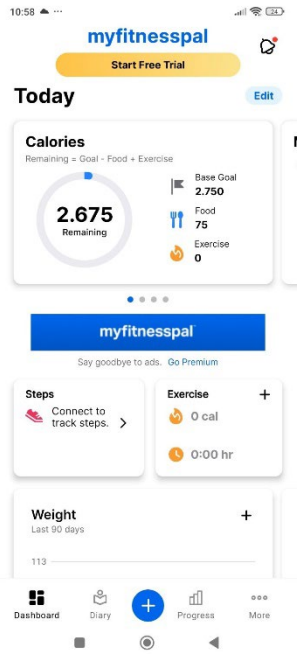


Fig. 1. *MyFitnessPal*

Lifesum

Launched in 2013, Lifesum helps users develop healthier eating habits through personalized diet plans and habit tracking. Similar to MyFitnessPal and YAZIO, it allows users to log meals via barcode scanning, manual search, or custom entry while tracking macronutrients, calories and weight progress [10]. Beyond standard nutrition tracking, Lifesum emphasizes an integrated approach to health by including more details, such as daily health advice, water intake and mood logging. The app offers a variety of meal plans directed to different dietary goals, including high-protein, ketogenic, Mediterranean, and intermittent fasting, providing structured guidance for users aiming to lose weight or improve overall well-being.

Lose It!

Lose It! nutrition app appeared in 2008, uses similar data input methods to MyFitnessPal, YAZIO and Lifesum. In addition, Lose It! has features such as simplicity, goal-oriented interface, group challenges and social motivation. The app provides progress graphs and goal forecasts, based on macronutrients, calorie intake, physical activity and weight changes [10].

Carb Manager

Carb Manager is made in 2010 and directed to specialized nutrition, i.e. low-carb, ketogenic, or other carb-restricted diets. Unlike the previously described applications MyFitnessPal, YAZIO, Lifesum or Lose It!, Carb Manager is focused on keto or diabetic-friendly diets [11].

CONCLUSION

This paper presented the overview and analysis of popular nutrition apps — MyFitnessPal, YAZIO, Lifesum, Lose It! and Carb Manager, concluding that each offers unique features catering to different user needs and preferences. Despite their growing popularity and potential

to support healthier eating habits, these digital tools are most effective when combined nutritional education. While nutrition apps can significantly assist users in managing their diets, they cannot fully substitute professional nutritional guidance and expert knowledge in personalized care.

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REFERENCES

[1] Kupusinac, A., Stokić, E., Doroslovački, R. Predicting body fat percentage based on gender, age and BMI by using artificial neural networks. Comput Methods Programs Biomed. 2014 Feb;113(2):610-9. doi: 10.1016/j.cmpb.2013.10.013. Epub 2013 Oct 29. PMID: 24275480.
[2] Obesity: preventing and managing the global epidemic. Report of a WHO consultation. World Health Organ Tech Rep Ser. 2000;894:i-xii, 1-253. PMID: 11234459.
[3] World Health Organization. One in eight people are now living with obesity, WHO, 2024. https://www.who.int/news/item/01-03-2024-one-in-eight-people-are-now-living-with-obesity
[4] Vrbaški, D., Vrbaški, M., Kupusinac, A., Ivanović, D., Stokić, E., Ivetić, D., Doroslovački, K. Methods for algorithmic diagnosis of metabolic syndrome. Artif Intell Med. 2019 Nov;101:101708. doi: 10.1016/j.artmed.2019.101708. Epub 2019 Oct 15. PMID: 31813488.
[5] Pujia, C., Ferro, Y., Mazza, E., Maurotti, S., Montalcini, T., Pujia, A. The Role of Mobile Apps in Obesity Management: Systematic Review and Meta-Analysis. J Med Internet Res. 2025 May 6;27:e66887. doi: 10.2196/66887. PMID: 40327853; PMCID: PMC12093073.
[6] World Health Organization. Healthy diet, WHO, 2020. https://www.who.int/news-room/fact-sheets/detail/healthy-diet
[7] European Food Safety Authority. Dietary Reference Values for nutrients: Summary report, EFSA, 4 December 2017, doi: 10.2903/sp.efsa.2017.e15121, https://www.efsa.europa.eu/sites/default/files/2017_09_DRVs_summary_report.pdf
[8] U.S. Department of Agriculture and U.S. Department of Health and Human Services. Dietary Guidelines for Americans, 2020-2025. 9th Edition. December 2020. https://www.dietaryguidelines.gov/sites/default/files/2020-12/Dietary_Guidelines_for_Americans_2020-2025.pdf
[9] International Diabetes Federation. The IDF consensus worldwide definition of the metabolic syndrome, 2006. https://idf.org/media/uploads/2023/05/attachments-30.pdf
[10] Rivera, J., McPherson, A., Hamilton, J., Birken, C., Coons, M., Iyer, S., Agarwal, A., Lalloo, C., Stinson, J. Mobile Apps for Weight Management: A Scoping Review. JMIR Mhealth Uhealth 2016;4(3):e87, DOI: 10.2196/mhealth.5115
[11] Wang, Y., Min. J., Khuri, J., Xue, H., Xie, B., A. Kaminsky, L, J. Cheskin, L. Effectiveness of Mobile Health Interventions on Diabetes and Obesity Treatment and Management: Systematic Review of Systematic Reviews. JMIR Mhealth Uhealth 2020;8(4):e15400, DOI: 10.2196/15400