

3D DESIGN AND IMPLEMENTATION OF SIMULATIONS BEFORE THE PROTOTYPE DEVELOPMENT: IMPORTANCE OF CIRCULAR ECONOMY INPUT ELEMENTS

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**Miloš VORKAPIĆ¹, Aleksandar JOVANOVIĆ², Miloš VASIĆ³,
Dragoljub TANOVIĆ⁴, Nataša ĐALIĆ⁴**

¹University of Belgrade, Institute of Chemistry, Technology and Metallurgy - National Institute of the Republic of Serbia, 11000 Belgrade, Njegoševa 12, Republic of Serbia

Corresponding author. E-mail: worcky@nanosys.ihtm.bg.ac.rs

ORCID ID (<https://orcid.org/0000-0002-3463-8665>)

²Edukons University, Faculty of Project and Innovation Management "Prof. Dr. Petar Jovanović" 11000 Belgrade, Bože Jankovića 14, Republic of Serbia

³Institute for Testing of Materials, 11000 Belgrade, Bulevar Vojvode Mišića 43, Republic of Serbia

ORCID ID (<https://orcid.org/0000-0002-5743-6038>)

⁴University of Belgrade, Faculty of Mechanical Engineering, 11000 Belgrade, Kraljice Marije 16, Republic of Serbia

ORCID ID (<https://orcid.org/0000-0002-7806-1458>)

⁵University of East Sarajevo, Faculty of Transport and Traffic Engineering, 74000 Doboje, Stefan Nemanja 5, Bosnia and Herzegovina

ORCID ID (<https://orcid.org/0000-0002-7613-4481>)

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This paper examines the numerical simulation within the circular economy framework. The numerical simulation of an electronics enclosure was analysed in two cases. The first case referred to the FEM analysis of the enclosure behavior under a uniform load applied to the cover and to the connection between the cover and the central part. Additionally, the impact of the enclosure striking a hard surface and its behavior after a fall were evaluated. The second direction concerned the application of the Slicer software platform, and the printing parameters were also defined. All preparations were made before the prototype was implemented. So, during design and after simulations, the designer can adjust the model's dimensions or redesign the existing product. This paper describes the strategy that designers should apply in the implementation of the redesigned product. Numerical simulations as an input element of CE reduce the risk of failed prototypes, and their importance is reflected in the rapid prototyping without loss of material or consumption of other resources, reliable analysis of prototypes, identification of critical zones, and the possibility of recycling planning. For comprehensive analysis and product certification, experimental testing and the use of recycled materials are required.

Keywords: Circular economy; Additive manufacturing; Numerical simulation; Electronic enclosure; FEM; Slicer.

INTRODUCTION

In additive manufacturing (AM), parts/ prototypes are built layer by layer. All devices that use this principle differ in the materials used, the technology for creating layers, and the way these layers are joined (Gibson et al., 2021; Han et al., 2023). AM has many advantages and disadvantages compared to classical manufacturing (CM). In this regard, CM leads the way in terms of production time, costs, and production volume;

that is, it is more oriented towards the production of large series (the average price per product is lower when production volume is higher). However, the disadvantages are evident in terms of prototyping speed and the initial costs of tools and molds. Therefore, AM is more suitable for the production of complex prototypes in small series or spare parts for end-user replacement (Matsumoto et al., 2016).

Prototyping is fundamental in the AM or 3D printing process. In this context, the prototype represents a quick and optimal solution because it saves time and money from the design stage through the overall product development process to the launch of production (Rasu, 2023). From the designer's perspective, AM offers a new approach to thinking and decision-making in product implementation (Attaran, 2017).

Unlike conventional (or traditional) manufacturing AM enables rapid design changes without the need for expensive specialized tooling or extensive prototype testing, while minimizing material waste, energy consumption, and production time (Abdulhameed et al., 2019). In prototyping, AM serves not only to verify a product's form but also to validate its performance under operational conditions. Murr et al. (2012) showed the importance of rapid prototyping and the implementation of bio-compatible structures in adapting to human anatomy. In the automotive industry, prototyping allows testing of ergonomics and functionality before mass production. Also, in the aerospace industry, prototyping enables the validation of complex geometries before production launch (Gisario et al., 2019).

Circular economy (CE) in 3D design and simulation execution implies applying the principle of sustainable production from the design phase onward and conducting digital testing of products. The goal is to reduce energy and material consumption and waste right from the start. The design and numerical simulation of the model proceed as follows: first, the model is designed and tested in a virtual environment, and then it is printed using 3D printing. Therefore, products are made through a digital and additive process (Esmailian et al., 2016). In these processes, the functionality, strength, and stability of the model are tested, to reduce design errors and material consumption, which is later reflected in the total manufacturing cost. In classic production, models with complex geometry make quick changes and modifications difficult. That is why it is important to simplify the geometry wherever possible (simplify the model and reduce mass) and to produce only those products that are current and urgent for production (Pongwisuthiruch & Potiyaraj, 2025).

In this paper, an important problem is highlighted. Therefore, a research question is also posed:

According to the principles of CE, how to eliminate the high rate of unsuccessful prototype development, and therefore the loss of resources, occur?

According to Gibson et al. (2021), a substantial number of failed models and prototypes can be attributed to complex geometries, non-optimized printing parameters, and issues related to material and interlayer adhesion. In this context, Wu et al. (2023) employed micro-computed tomography (micro-CT) to examine the internal structure of the material. Their analysis revealed the presence of gaps within the material and insufficient bonding between layers. These findings indicated that the press parameters had been poorly adjusted, with speeds and temperatures exceeding the permissible limits.

During 3D printing, defects may appear, affecting the mechanical properties of the developed samples or prototypes. Key parameters such as printing speed and temperature directly affect the appearance of defects and the quality of the interlayer connection (so the thickness of the layer is also important), and this was confirmed in the work of Kumar et al. (2023). A common problem that occurs during printing is the wateriness and inadequate adhesion of the layers. On the example of composite structures with reinforced fibre mesh, Ashebir et al. (2024), observed porosity, delamination and interlayer bonding, which results in a in mechanical performance degradation.

The purpose of this work is to integrate 3D design into CE using numerical simulations. Methodologically, these are the input steps that would be considered through the elements of the R model.

The scientific contribution of this work should be defined in terms of improving the efficiency of numerical simulation applications and increasing their predictive accuracy in the context of AM. The importance of simulations in the early design phase enables the timely identification of potential errors and optimization of printing process parameters. This considerably reduces the number of unsuccessful prototypes, thereby lowering the carbon footprint. From an industrial standpoint, the work is significant for improving production by optimizing the production cycle, shortening the time to product development and launching production.

LITERATURE REVIEW

Numerical simulation (NS) represents digital testing and optimization of the model before its implementation. It enables the prediction of the mechanical, thermal, and production behavior of the model, which significantly increases the success of the production itself. In general, digital design and NS within the framework of CE implies that the product lasts as long as possible (to remain in use as long as possible, i.e. to become a resource again and not waste), that it is easy to disassemble and assemble, that the materials can be reused or recycled, i.e. that the consumption of energy and resources is as low as possible (Wu et al., 2023). Within CE, computational optimization in design is very important for finding the best solutions in selecting the optimal design (Ortner et al., 2022).

The process begins with a prototype design (or 3D model) in one of the available CAD software. At this stage following is defined: the dimensions and shape of the product, the material to be used, and the construction and function of the parts. For prototypes with complex geometry, AM enables minor modifications or major design changes. After creating a digital 3D model, a NS of its behavior under different conditions is performed. NS make it possible to test the model under conditions difficult to replicate in the laboratory, such as maximum loads, vibrations, and shocks.

According to research in the field of AM, simulations enable the prediction of material and structural behavior during the printing process and in the exploitation phase (Gibson et al., 2021). One of the most important advantages of simulation is the ability to analyze mechanical stresses and deformations within the model. With numerical analysis methods, such as the Finite Element Method (FEM), it is possible to identify critical points in the construction and optimize the design before construction. In this way, the probability of product breakage or deformation during use is reduced (Rosen, 2014). This step is very important, because errors are only discovered after printing.

In addition to the FEM analysis, topological optimization of the structure is also important, as it analyzes the use of material and its retention in areas where the integrity of the structure is not compromised. With the optimization of the geometry and proper distribution of materials, an efficient, lighter, and, according to mechanical

characteristics, reliable product is obtained. This kind of analysis is especially important in industries where weight and efficiency are key factors, such as the aerospace and automotive industries (Ashby, 2012).

Another important advantage of simulations relates to the analysis of thermal processes during 3D printing. During printing, the material heats up and cools down, which can cause deformation, shrinkage, or cracking. Various simulation models enable the prediction of such phenomena and the adjustment of printing parameters, all to avoid printing errors (Ngo et al., 2018). Simulations greatly reduce the need for a large number of physical prototypes. This supports the principles of CE and more efficient use of resources (Geissdoerfer et al., 2017).

NS are important for optimizing the 3D printing process and providing a clear understanding of the phenomenon of mutual bonding between material layers within the structure. In the paper (Matúš et al., 2023), a virtual model was first analyzed, followed by a NS using the FEM. The authors showed how different press process parameters influence changes in mechanical characteristics. According to Paul (2021), FEA has great potential to improve the 3D printing (FDM) process. FEA analysis has significant potential to improve the 3D printing process. This method also analyzes the quality of parts and the potential to reduce costs.

Sung et al. (2023) investigated the influence of topological optimization on elements produced by additive manufacturing. In this research, optimization guidelines are given to improve the performance, reliability, and profitability of 3D printing. Dey et al. (2020) optimized several defined parameters of 3D printing using the PSO (Particle Swarm Optimization) method. Research has shown that when the correct selection of printing parameters is used, mechanical performance and printing quality can improve, resulting in reduced defects and shorter production time, in accordance with CE.

RESEARCH METHODOLOGY

Model creation process

AM includes the use of various thermoplastic materials. If the concept of CE is followed, the advantages of using AM in the 3D printing process include reduced material use, reduced design and

production time, and reduced mass of realized parts/elements (Ford & Despeisse, 2016). In the structural context, 3D printing has disadvantages in terms of strength and the need to add material during prototyping (Jiang et al., 2018). In this

context, the methodology for 3D simulation before prototyping the electronics enclosure for printing should follow the steps outlined in Table 1.

Table 1: Methodological approach in the implementation process

Activity	Notes
3D CAD implementation and correction	The model is implemented by using 3D CAD software. This step allows changes to the model before it goes into production.
STL conversion	All 3D printers use an STL file. The 3D model is imported as an STL file into the specialized Slicer program.
Model slicing and G-code generation	Slicers integrate hardware, software, and materials to achieve high-quality results and support various file formats. Changes can be made to the printing parameters as well as to raise or reduce the 3D model.
G cod simulation	Slicer software generates a G-code that the 3D printer recognizes. G-code is a standard format used to encode: 1) the movement of the printer extruder, 2) the charge of extruded material, and 3) the speed of the extruder movement.
3D model print	G - cod is loaded into the printer, and the model is ready for printing.

STL conversion and usage of the Slicer software

Converting a virtual 3D model into an STL file is a basic step in additive manufacturing. The analyzed, refined, and completed 3D model is exported as an STL file. This conversion marks a key step in the 3D printing process, as it transitions the model from a digital (virtual) form to a physical implementation. So 3D printers use this format to create a model layer by layer. The STL format simplifies the model by decomposing its surface into a series of triangles (King et al., 2021; Zhou et al., 2024). However, the quality (or resolution) of the STL file depends on the triangle size. The smaller the triangle, the better the resolution (Zha & Anand, 2015).

Also, problems with STL files are reflected in inverted normals or the geometry of complicated edges. Precisely because of such anomalies, many software packages for cutting models include functions for automatically repairing and removing such problems, so that designers can optimize STL formats. The use of Slicer software enables detection before the press itself: potential fractures or deformations, support problems, parts that will not form properly or fit together, or that are deformed during cooling (Manmadhachary et al., 2016).

NS before 3D printing

Before the conversion to the STL format, many CAD software applications enable virtual

simulations that are crucial for the design and analysis of the future product. prediction of real material behavior, optimization of geometry and structure, reduction of prototypes and waste, better preparation for FEA analyses, and subsequent use of the product (Zhang et al., 2019). In this step, NS serves as an input tool within the CE framework. An important division of simulations in 3D printing comes down to material, process, and geometry.

For this reason, the following are mostly used: thermal simulation to analyze temperature changes during printing, simulation of deformation and shrinkage, mechanical simulation, simulation of the printing process, and simulation of topological optimization, which is gaining increasing importance (Behseresht & Park, 2024; Jiang, 2024).

In topological simulation, special focus is placed on reducing the model's mass while maintaining strength and load-bearing capacity through design optimization (Trovato et al., 2023). This shows that lighter components can be produced without sacrificing functionality or production time. Impact simulation before and after the printed model is implemented is very important, because the main goal is to withstand real loads.

Impact simulation after the development of the electronics enclosure prototype is described in detail in the paper (Vorkapić & Ivanov, 2022). The impact simulation, recorded by high-speed

cameras, captured the actual behavior of the materials and construction in a free fall from a height of 6m. By impact simulation, it is clearly seen where stress concentrations or delaminations occur between layers, as described in detail in the paper (Daiyan et al., 2012). In this way, the risk of failed prototypes or damage in use is reduced. Simulation results are significant for 3D printing, including wall thickness, layer geometry and orientation, material selection, and printing technology.

CE connection with the NS

CE aims to reduce waste and extend the product's life cycle. The connection with NS indicates that

the majority of designers/engineers must respect CE principles to reduce weight without compromising strength (Mesa, 2023). On the other hand, simulations help plan the recycling and reuse of materials, especially in AM. In Table 2, the connection between CE and NS is given.

Because of all of the above, CE should include modular design, easy product disassembly, and recycling of as many components as possible. When the NS is integrated with the CE approach, one can move on to production planning. In Table 3, the connection of the R principle of CE with NS is given.

Table 2: Aspects of CE and examples of application of NS

CE	NS	Application
Prediction of material behavior	<ul style="list-style-type: none"> - FEM. - Topological optimization. - Dynamic simulations 	Material strength and wear analysis before manufacturing.
Optimization of the manufacturing process	<ul style="list-style-type: none"> - Process simulation. - Energy simulation. 	<ul style="list-style-type: none"> - Testing manufacturing processes, - Material recycling
Product design according to CE principles	<ul style="list-style-type: none"> - CAD/CAE integration. - Modularity simulations. 	<ul style="list-style-type: none"> - Modular design. - Easy disassembly. - Planning of recycling.
Additive manufacturing and 3D printing	<ul style="list-style-type: none"> - Press simulation. - Thermal and mechanical analysis. 	<ul style="list-style-type: none"> - Planning the best orientation, additional material, reduction of material.
Product life cycle evaluation	Life Cycle Assessment with embedded simulations.	<ul style="list-style-type: none"> - Prediction of wear and replacement of components.

Table 3: Connection between R principles and simulations

Activity	Connection	R principles
Model simulation	High	Refuse - The simulation shows where the unnecessary use of material appears (wall thickness, auxiliary material).
		Reduce - Various optimization methods and tools can be used to reduce time, materials, and energy, which minimizes waste.
		Recycle - The simulation predicts how much material can be recycled and in what way.
Simulation support	Medium	Reuse - The simulation predicts which parts can be easily replaced and reused.
		Refurbish - Simulation is used to test the integration of old parts into a new model or product.
		Remanufacture - Simulation models can be optimized or modified by using old parts to form new products.
		Recover - Simulation of energy consumption and remaining materials in recovery planning.
Creative work	Low	Repair - It depends more on physical work.
		Rethink - Simulation enables testing of different designs and processes before implementation.

For designers (engineers or managers) using NS, the flow of process management would take place in the following stages: 1) optimization of the production process; 2) resource management and

waste reduction; 3) increasing profitability through faster decision-making; 4) CE and operational support; 5) improving quality control and reducing risk; and 6) supporting strategic planning. NS

before 3D printing enables digital testing of prototypes in the CE concept. The connection of CE with NS provides the following benefits, which are reflected in: waste reduction (optimization of resources is carried out), product reuse that comes to the forefront due to market needs, efficient

recycling (recovery of resources using recycled material), and increased flexibility (through innovation in design). In this regard, Table 4 presents the connection between the R principle and managerial skills in the management of NS, in line with the purposes of CE.

Table 4: Connection between R principles and manager skills

R	Manager skills	Note
Refuse Reduce Rethink	Managers use NS to implement unnecessary materials and components before launching production.	Overproduction is reduced.
Reuse Remanufacture Refurbish	Managers gain insight into the product life cycle. They can plan strategies to recover materials through product redesign and recycling.	Modular design permits easy assembling and disassembling of components. Some of the components can be used in other products. In this way, the costs of purchasing new materials or realizing new products are reduced.
Recycle Recover	NS allows predicting material flows and considering how to recycle or recover the material after use.	/
Rethink Repair Repurpose	Managers test different product variants using NS.	Digital prototypes allow for changes over multiple iterations. It is also possible to evaluate the environmental impact before actual production.

For industrial applications, NS are very important before production launch, as they enable processes to be tested and optimized in advance. Computer-aided design (including shape optimization and choosing adequate materials) plays a key role in reducing waste. NS enable virtual testing without the need for physical prototypes (Gamdha et al., 2025). Savings are already visible at this stage; waste is avoided, and resources are saved because experiments are not conducted. However, it should be noted that the design process, as well as the work in many previous simulations, requires specialized software and professional staff.

IMPLEMENTATION OF THE ELECTRONICS ENCLOSURE

The paper analyzed the prototype of the electronics enclosure for the temperature sensor. The essential parts of the enclosure were shown in Figure 1: 1) cover with a hole, 2) transparent glass (acrylic), 3) Zeger safety fuse, 4) O-ring, 5) brass inserts, 6) central part, and 7) cable Pg connector (Pg 13.5). A transparent glass is placed over the hole of the cover to allow data to be read from the electronic display. AM allows the use of other non-plastic materials. The joining of two or more parts into a single unit is made possible by fastening elements such as screws and nuts (see Figure 1).

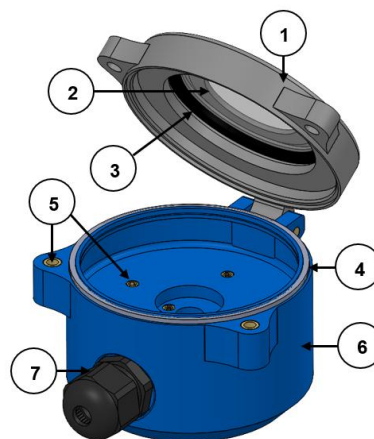
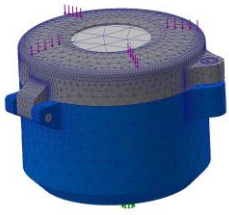
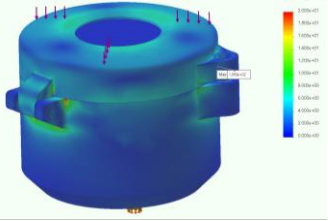
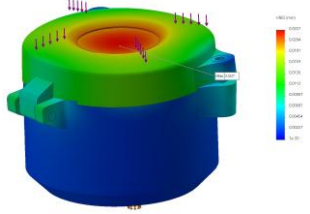
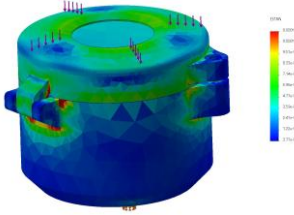
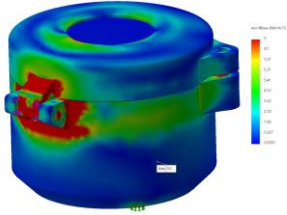
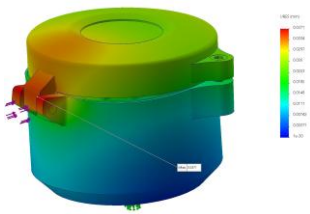
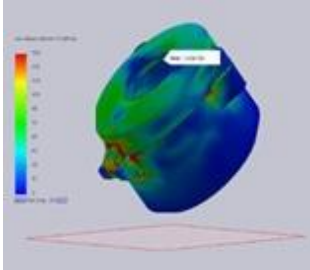


Figure 1: Virtual 3D model of the electronics enclosure

NS was applied in two directions. The first direction was concerned with the analysis of the enclosure's behavior when uniformly loaded on the cover and at the connection between the cover and the central part. The fundamental idea was to analyze all critical areas and zones affecting the enclosure's integrity. Also, the impact of the enclosure on a hard surface and its behavior after dropping were analyzed; see Table 5.

Table 5: Application of NS using the FEM

<ul style="list-style-type: none"> - The generated finite element mesh is shown. - Simulations were done using the finite element method (FEM). 	
<ul style="list-style-type: none"> - Load: forces acting on the cover surface (arrows) - Support: the bottom of the central part of the enclosure is fixed. - It can be seen that the greatest load is transferred by compression of the sealing rubber and transferred to the hinge support. - It is possible to show the effect of force through animation during the NS, thereby obtaining a clearer picture of how the load and deformation of the assembly elements develop. 	
<p>Display of the deformation ratio when the force is applied uniformly to the cover. The largest deformation is present in the middle of the cover.</p>	
<p>Display of the ratio of deformation energy on parts of the assembly when the force is applied uniformly to the cover.</p>	
<ul style="list-style-type: none"> - Distribution of stress in the assembly elements when the force is applied at the connection cover - the central part of the electronics enclosure. - Here, it is possible to create an animation of the stress distribution display when a greater force is applied to the connection between the cover and the central part. 	
<p>Distribution of deformations during the action of lateral force on the connection cover - the central part of the electronics enclosure.</p>	
<p>Simulation of the impact of an enclosure on a rigid surface from a height of 1m. During the animation, changes in the stress state of the assembly elements are clearly observed, along with self-oscillations induced by the impact.</p>	

The second direction concerned the application of the Slicer software platform, in which the printing parameters are defined, and the final preparation is carried out before the prototype is developed. It is remarked that the virtual CAD model is converted into a physical prototype on a 3D printer. During the design process and subsequent simulation analysis, the designer can modify the dimensions or redesign the product to improve its performance and functionality. The virtual CAD model is converted to an STL file, which is essential for the

Slicer software platform. The appearance of the electronics housing elements before printing in the Prusa Slicer user program is given in Figure 2. From the image, you can see the contours of the main structure (orange and red colors) and auxiliary structures (fillers - light and dark green colors). Generally, in the Slicer program, the important analysis parameters are: printing and plate temperature; layer height; print speed; infill density; and infill orientation.

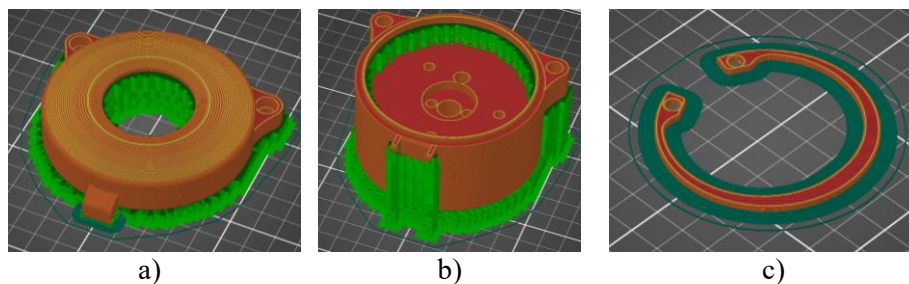


Figure 2: Basic elements of the electronics enclosure before printing: a) cover; b) central part, and c) Zeger safety fuse.

After describing, analyzing, and controlling the printing parameters and selecting the material, the STL file is converted to G-code, and the prototype is inspected by moving the virtual nozzle. The original Prusa i3MK3S+ printer and white PLA filament were used in the work. The printing parameters for the electronic enclosure are given in Table 6.

The first layer is set to 0.2 mm by the software, while the others are printed with a thickness of 0.15 mm. The implemented prototype, after being removed from the plate, is additionally cleaned of auxiliary material and then undergoes additional processing. Rest material is collected in a designated area that serves as a repository for useful waste for recycling, all in accordance with

CE principles. Figure 3 shows the completed electronics enclosure with added material.

Table 6: Defined parameters before printing

Parameter	Value
Layer Height	0.15 mm
Wall Line Contour	3
Top Layers	3
Bottom Layers	3
Printing Temperature	215°C
Build Plate Temperature	60°C
Printing Speed	50 mm/s
Travel Speed	60 mm/s
Infill Density	45%
Infill Orientation	-45°/+45°

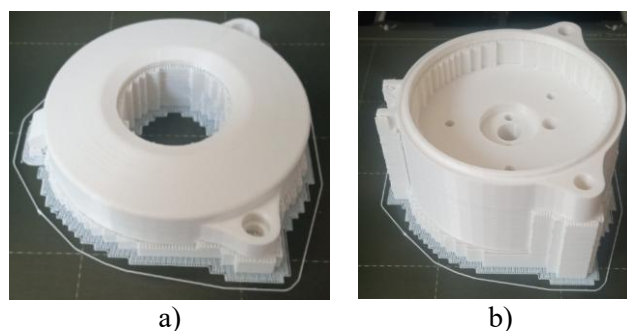


Figure 3: Form of the printed elements: a) cover with a hole and b) central part

The masses of all enclosure components are shown in Table 7. Measurements were made on a KERN

technical scale with an accuracy of ± 0.01 g. The printing parameters can be reconsidered based on

the given data. It can be seen that the portion of additional material in the enclosure's implementation varies with the geometry. However, this can lead to increased material consumption and greater waste accumulation.

Table 7: Enclosure manufactured parts weights

Enclosure part	Full weight [g]	Clean part [g]	Waste [g]
Cover	123.00	81.84	21.16
Central part	58.08	30.04	28.04
Zeger ring	3.36	2.15	1.21

RESULTS

Simulations were conducted to analyze the behavior of the enclosure under uniform loading of the cover with a hole. The hole position is critical, especially near the hole edge. It was considered that the rib should be used because it reduces tension. Also, the connection between the cover and the central part is critical, and other scenarios are considered here also. The mesh density was analyzed, and it was concluded that a finer mesh is preferred because it indicates potential stress concentration, which is important for further analysis.

The highest stress concentration occurs at the junction between the cover and the central part of the enclosure because of abrupt geometric discontinuities and local stiffening effects. This region is the critical location for fatigue initiation and indicates inadequate material utilization. Numerical analysis of the strain energy distribution shows that the highest concentrations are around the joint, where damage or breakage may appear. This critical zone is important for later decisions regarding joint reinforcement or design optimization. Precisely from this point of view, the distribution of stress in the elements of the assembly was analyzed when the load was applied directly to the joint cover - the central part of the enclosure. The highest stress values occur in the space around the cover's connecting elements and in the central part. The simulation identifies this zone as critical due to the risk of deformation and damage.

DISCUSSION AND CONCLUSION

AM within CE is gaining increasing importance for saving resources, reducing waste, and reducing production time. AM ensures rapid design changes

by leveraging product modularity and reducing material overuse through recycling. A NS of the electronics enclosure showed the highest stress concentration at the connection between the cover and the central part ("hinge"). The joint proved to be a critical location where material fatigue and possible deformations can occur. The energy analysis of the deformations indicates that the greatest load is transmitted through the rubber ring and the hinge support.

NS incorporated in CE provides a framework for improving manufacturing efficiency using AM. Checking the design and process parameters at an early stage, and later through the application of NS, reduces uncertainty in production from the development of unsuccessful prototypes to minimizing waste. By applying NS, the product's performance throughout its life cycle can be predicted. Designers are recommended to develop products with longer life cycles, which means easier replacement of parts, quick repair, simple maintenance, and the possibility of recycling parts, all in compliance with the R principles of CE. It means that NS plays a crucial role in sustainable development strategy, focusing on optimizing production time, material consumption, and total operating costs.

Based on the presented example, there is a strong connection between NS and CE. The following CE aspects were mentioned: prediction of material behavior, process optimization, design implementation, product implementation using 3D printing, and product life cycle analysis. Prediction of material behavior can be easily reached through FEM simulation, topological optimization, and thermal and mechanical analysis. Process optimization refers to platforms that test processes and primarily use process or energy simulations. Completion and treatment of the design comes down to CAD/CAM integration and modularity analysis. The Slicer software provides a simulation of the press and allows planning of orientation and the use of additional material while reducing waste. In the end, the analysis of the product's life cycle entails assessing the design from the perspectives of durability, wear and tear, and timely replacement of parts.

The key contribution of this work is the establishment of a systematic approach that integrates numerical simulations and principles of CE in AM, enabling designers to predict material behaviour, optimise processes, and minimize

resource consumption at an early stage of designing.

This paper describes the strategy designers should assume to adapt to the complex needs of end users and rapid market changes. This approach can also be applied in the implementation of a redesigned product. NS as an input element of CE reduces the risk in the implementation of failed prototypes, and its importance is reflected in the following:

- Fast prototypes are produced without any loss of material or other resources. In this stage, the designer is responsible for market-related interventions and changes.
- Reliable prototype analysis enables further refinement and optimization of the existing design.
- Identification of critical zones, optimization of geometry, joints, and gaps.
- The possibility of planning recycling and using modular design to reduce waste and energy consumption.
- In the manufacturing process, fine-tuning of press parameters is required to achieve high-quality mechanical properties of the product.

The application of NS has advantages when making strategic decisions before the manufacturing process. In this case, engineers or managers can accurately plan material flow and launch production in a timely manner. The savings in the production cycle alone indicate that material savings of 20%–30% are possible. From a managerial standpoint, rationalizing materials and energy use is important, leading to reduced carbon footprint and total costs. NS enables managers to predict performance during exploitation, including load, vibration, and temperature changes. In this sense, engineers (mainly managers) design modular products that directly affect durability, sustainability, and environmental efficiency, which is the key to the CE principle.

Future research should focus on experimentally validating the proposed simulation model under real AM conditions. Particular attention should be given to comparing simulation and experimental results, especially regarding mechanical properties, interlayer adhesion, and dimensional accuracy.

Further research should investigate the use of recycled materials in AM, evaluating their performance through numerical simulations and experimental tests. The development of more advanced simulation models should incorporate

process variability, thermal effects, and material anisotropy to reduce the gap between virtual predictions and actual production results.

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3D PROJEKTOVANJE I PRIMENA SIMULACIJA PRE IZRADE PROTOTIPA: ZNAČAJ ULAZNIH ELEMENATA CIRKULARNE EKONOMIJE

U radu je razmatrana primena računarskih simulacija u okviru koncepta cirkularne ekonomije. Računarska simulacija kućišta elektronskog uređaja razmatrana je u dva slučaja. Prvi slučaj odnosio se na FEM analizu ponašanja kućišta pri ravnomerno raspoređenom opterećenju na poklopcu i na spoju između poklopcu i centralnog dela. Analizirano je stanje kućišta pri udaru o tvrdu podlogu, kao i njegovo ponašanje nakon pada. Drugi deo istraživanja odnosio se na primenu softverske platforme Slicer. U ovom delu definisani su parametri štampe i izvršene su sve pripreme pre izrade prototipa. Na taj način, tokom projektovanja i nakon simulacija, projektant može prilagoditi dimenzije modela ili izvršiti redizajn postojećeg proizvoda. U radu je opisana strategija koju projektanti treba da primene u realizaciji redizajniranog proizvoda. Računarske simulacije, kao ulazni element cirkularne ekonomije, smanjuju rizik od neuspešne izrade prototipa, a njihov značaj ogleda se u brzom izradi prototipa bez gubitka materijala i potrošnje drugih resursa, pouzdanoj analizi prototipa, identifikaciji kritičnih zona i mogućnosti planiranja reciklaže. Za kompletnu analizu i sertifikaciju proizvoda potrebno je sprovesti eksperimentalna ispitivanja, kao i koristiti reciklirane materijale.

Ključne reči: Cirkularna ekonomija; Aditivna proizvodnja; Računarske simulacije; Kućište elektronskog uređaja; FEM; Slicer.