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APPLICATION OF THE 10R STRATEGY AND 7S TOOLS IN THE DEVELOPMENT OF WEARABLE SENSORS

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Original Scientific Paper

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This paper presents the integration of the 10Rs of the circular economy (CE) strategy with the 7S tools of Lean manufacturing, and lifecycle management of wearable sensors. The presented algorithm, based on CE, and the application of additive manufacturing (AM) in the realization of a modular enclosure from biodegradable polymer material, demonstrate a strategy for the sustainable development of prototypes with low material waste, rapid design changes, ease of disassembly and assembly, reuse, repair, and revitalization. The stated algorithm closes the circle between design, use, maintenance, and end-of-life of a product, incorporating sustainability into everyday engineering decisions through the example of wearable sensors. The electronic enclosure shown in the work is compact; it can be worn around the waist or secured to the head with a flexible tape. The results showed that the 10R/7S connection raises the enterprises' competitiveness through efficient production, extended product life, and reduced waste, while simultaneously addressing challenges such as regulatory observation, affordability, and user feedback after long-term product use. The study confirms a practical methodology for applying CE principles to wearable sensor systems and highlights opportunities for modular improvements, serviceability, and the use of environmentally friendly materials. The work contributes to engineering and product design by gathering sustainable product development and more effective product lifecycle management.

Keywords: 10R strategy; 7S tools; Circular economy; Additive technology; Wearable sensors; Body temperature.

INTRODUCTION

This study asks how effectively an integrated 10R strategy and 7S tools can be operationalized in the development of wearable sensors to close the loop between design, use, maintenance, and reuse within a Circular Economy (CE) context. We hypothesize that applying the 10R/7S algorithm to a wearable temperature-sensor prototype will enable practical design-for-disassembly and modular substitution of the sensing, MCU, and power blocks, and that biodegradable or recyclable enclosures combined

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with additive manufacturing will support low-waste realization. To test this, we implement a minimalist sensing chain (sensor → MCU → BLE → client app) with a dedicated service interface for recharging, firmware updates, calibration, and diagnostics, and evaluate whether these choices measurably support reuse, repair, refurbishment, and remanufacture.

Table 1: 7S tools

Element	Action	Notice
Sort	– Inspect the entire workplace, warehouse areas, and auxiliary rooms. – Identify unnecessary and redundant items, then move them to a specified location. – Label and separate necessary and unnecessary materials, tools, and equipment.	– The enterprise should retain only what is necessary and eliminate all unnecessary equipment and materials from the workplace.
Set in order	– Mark important items and give them priority. – Arrange and organize items in their selected places. – Achieve a visual inspection.	– Important items should be placed in their proper locations (everything necessary, based on its level of importance and priority, must be accessible, while everything unnecessary must be stored elsewhere).
Shine	– Identify and eliminate sources of mess in the workplace. – Keep machines, tools, and the workspace clean and organized. – Prevent further contamination and accumulation of unnecessary	– The workplace must always be kept clean, free of excess discarded materials, dirt, and disorder.
Standardization	– Implement standards (procedures and rules) to improve the visibility of inventory, work/consumable tools, and equipment. – Introduce the standards to employees. – Verify the traceability of the standards with practical examples.	– The enterprise must standardize processes and procedures to improve workplace operations, as this reduces the possibility of mixing all active elements in the work process, as well as the time spent searching for them.
Sustain	– Enhance employee motivation and enthusiasm. – Emphasize employee self-discipline.	– Performance deviations should be monitored. – Attention should be built among employees so they can contribute to maintaining a pleasant and safe work environment.
Safety	– The enterprise must comply with legal procedures related to safety standards. – Safety measures at the workplace and employee health protection measures must be implemented to ensure a safe and healthy work environment. – The enterprise needs to pay attention to safety, as well as the handling and disposal of waste.	– The enterprise must implement a comprehensive safety system that includes measures to prevent injuries and serious accidents in the workplace. The focus is on cleaning and organizing the work area.
Spirit	– Promote teamwork. – Provide communication at all levels of the enterprise.	– Encourage teamwork to increase employee productivity.

CE is a concept expressed through three main principles (Ciano et al., 2025; de Oliveira & Oliveira, 2023): 1) preservation and control of stock and renewable resources, 2) optimization of natural resource use through the circulation of materials, products, and their components, and 3) encouragement of efficiency in the production system through continuous monitoring and elimination of negative scenarios from the very beginning to the end of the product's lifecycle. On the other hand, Lean Manufacturing (LM) is a set of principles designed to eliminate waste. The application of the 7S tool (the basic 5S + Safety and Spirit) within LM is intended to support workplace management by creating a well-organized, efficient, orderly, and safe work environment (Cichocka, 2018).

The essence of the 7S tool (or concept) is viewed as a system that strives to improve the quality of management through better communication flow - both at the workplace/shop floor level (Filip & Marascu-Klein, 2015; Manzanares-Cañizares et al., 2022) and in terms of the overall information flow (monitoring, evaluation, and control) at the organizational level. All of this aims to ensure a favorable working environment and overall enterprise efficiency (Mahlaha et al., 2020). According to Salibi et al. (2022) and Xuan et al. (2025), the 5S tool enables the prevention of disorder in the workplace, and its implementation within the Circular Economy (CE) leads to improvements in working conditions, as well as enhanced monitoring of employee behavior. According to the authors, adopting 5S tools is essential for enterprises and serves as a practical starting point for implementation. If the elements of this tool are implemented in a planned manner, it leads to a faster-operating production system and a more efficient supply chain function. Furthermore, employees must be fully involved in all production and organizational processes. Table 1 presents the importance of each S element, according to many literature sources (Agrahari et al., 2015; Joshi, 2015; Mahlaha et al., 2020; Fernández Carrera et al., 2021).

According to Cichocka (2018), the first five elements of the 7S tool align with the goals of the Circular Economy (CE) and are analyzed through the following activities:

– Waste reduction – achieved by identifying and eliminating waste starting from the workplace, and later extending to all organizational levels;
– Timely and efficient use of resources – accomplished through standardization and improved workplace organization; and
– Environmental significance – energy consumption and waste accumulation are reduced.

The 10R principles within the concept of CE can be characterized as a set of strategies and techniques focused on "Smarter product production and smart use of materials" (Ciano et al., 2025). The principles allow the extension of product life cycles, encourage innovation in design, optimize costs/resources, and reduce negative environmental impact. Table 2, according to literature sources (Morseletto, 2020; Nosková, 2025; Prieto-Sandoval et al., 2018), presents the 10R principles of the CE strategy.

Table 2: R principles of CE

R	Name	Description
1.	Refuse	Products are not sustainable or have a negative environmental impact.
2.	Rethink	Reviewing the idea, concept, defined processes, work methods, and implementation procedures.
3.	Reduce	Minimizing the use of resources, materials, and energy from nature, as well as waste disposal.
4.	Reuse	Using a product that still functions and manages to fulfill its original function.
5.	Repair	Repairing a defective product so that it serves the same purpose or provides the same function.
6.	Refurbish	Overhauling a product with continuous improvement while maintaining product quality over an extended life.
7.	Remanufacture	A strategy related to the reproduction of used parts.
8.	Repurpose	Use products or components for a different function than originally intended.
9.	Recycle	A recycling strategy involves using recycled materials and waste by-products.
10.	Recover	Extract energy or materials from products at the end of their life

The 10R strategy model, when combined with the 7S tool, holds multiple advantages for modern sustainable manufacturing. With the 7S tool, risk is reduced (through waste minimization), safety is increased (via resource optimization), and the importance of ergonomics and the working environment is enhanced (Filip & Marascu-Klein, 2015; Sasso et al., 2025). Table 3 presents the importance of both concepts in reaching a more efficient, cleaner, and environmentally friendly production process, in line with the proposed CE policies (Antoniadou, 2024; Ciano et al., 2025; Sukdeo et al., 2020).

Table 3: Contribution of Concepts to Sustainable Production

Concept	Element	Contribution
10R	CE	It is essential in product design, especially when it comes to recycling, reuse, and extending the product's lifespan.
7S	LM	A tidy, clean, and safe workplace is created as a result.

To situate our work within existing research, we briefly review recent studies on sustainability assessment in digital health technologies. Among recent contributions, (Quisbert-Trujillo & Vuillerme, 2025) introduce a three-stage Health Technology Sustainability Assessment framework for IoMT that integrates life cycle assessment with eco-design and cost–economic evaluation to support early, pragmatic design decisions. They illustrate this approach on smart inhalers for COPD using pressure-drop sensing and three alternative electronic module designs, modeling production costs and global-warming impacts to compare policy options and projected savings. Furthermore, (Sunstrom & Sunstrum, 2025) review wearable on-body drug delivery devices for large-volume subcutaneous biologics, synthesizing device design, clinical use, and US/EU regulatory perspectives. Their review explicitly addresses environmental sustainability by noting the waste burden of single-use formats while describing modular, recyclable or semi-reusable architectures and manufacturer take-back programs that can reduce life-cycle impact, and it anticipates greater digital integration and eco-design strategies in future systems.

Complementing the above, Skrzetuska & Rzeźniczak (2025) review circularity challenges for smart textiles and flexible electronics, emphasizing end-of-life hurdles caused by hybrid material stacks. They survey key applications and fabrication routes, then propose eco-design measures, design-for-disassembly, modular architectures, minimizing hazardous or hard-to-recycle materials, and manufacturer take-back programs, to reduce life-cycle impacts.

In parallel, a review of flexible wearable sensors for cardiovascular monitoring surveys modalities for heart rate, blood pressure, blood oxygen saturation, and glucose, and classifies devices by sensing principle and materials that enable comfort and long-term wear; however, it underscores persistent hurdles for real-world deployment, including motion artifacts, wireless and power constraints, and the need for integrated algorithms to enhance diagnostic utility (Chen et al., 2021). Complementing these overviews, washable textile-based piezoresistive patches that combine gold-nanowire-impregnated cotton, screen-printed silver electrodes on nylon, and Parafilm encapsulation demonstrate ultrahigh sensitivity, fast response and low detection limit, along with durable performance after multiple machine-wash cycles, capturing breathing, pulse, heart rate and joint motion for practical health monitoring (Zhao et al., 2022). Furthermore, polymer-assisted layer-by-layer self-assembly yields conformal, flexible and multifunctional thin films on diverse substrates for continuous physical, chemical and biological sensing, while identifying open challenges such as long-term stability, biocompatibility, data acquisition and scalability, with spray-assisted and roll-to-roll routes noted as promising (Jin et al., 2024).

From a lifecycle perspective, a narrative review maps the wearable product system from materials and manufacturing through distribution, use and end-of-life, and proposes eco-design implications grounded in circular-economy thinking, including design for disassembly, cradle-to-cradle strategies, modularity, repair and closed-loop recycling (Gurova et al., 2020). Likewise, an ISO 14040-guided assessment of a printed hybrid NFC gas-sensor tag quantifies how bio-based substrates, copper inks, screen printing with intense pulsed light curing, and recycling can reduce global-warming impacts, while the silicon chip remains the dominant hotspot, thus directing attention to architecture choices and end-of-life planning (Zikulnig et al., 2025). An early-stage assessment of a wearable microfluidic sweat-rate sensor further shows that replacing silver screen-printed electrodes with copper laminates or screen-printed graphite lowers production-phase impacts without sacrificing function, using LCA as a design tool to steer material selection during development (Rabost-Garcia et al., 2025). Moreover, a focused review of end-of-life solutions for electronics-based smart textiles highlights the scarcity of standardized waste pathways and legislation, and calls for early end-of-life planning, design for disassembly, and harmonized standards that integrate electronic and textile waste streams (Veske & Ilen, 2020). In addition, an eco-friendly, low-power temperature sensor based on a water-processable gelatin–graphene nanocomposite demonstrates indoor environmental monitoring with simple operation, suggesting opportunities for benign materials and low-energy operation in sustainable wearables (Landi et al., 2022). Building on a laser-induced graphene (LIG) resistive respiration platform with custom adjustable-current electronics for real-time abdominal breathing (Ilić et al., 2023), subsequent work explored SpO_2 estimation from chest-worn LIG signals using feature extraction and learning models (Koteska et al., 2024). The simple LIG fabrication point to eco-design opportunities with modular electronics, replaceable bands/sensors, and pathways for repair or refurbishment, that align with lifecycle thinking and supply-chain circularity of this wearable system in the future. Therefore, for further research, the following research question appears:

How can a display strategy be developed, implemented, and experimentally validated that operationalizes the 10R Circular Economy (CE) strategy in combination with the 7S Lean manufacturing tools for the sustainable design, production, and lifecycle management of wearable sensor systems?

RESEARCH METHODOLOGY

The integration of the 10R circular economy (CE) strategy with the 7S tools of Lean manufacturing and lifecycle management is illustrated by an algorithm (Vorkapić et al., 2024); see Figure 1. The algorithm includes additive manufacturing (AM) as a key factor in wearable sensor realization. This algorithm provides high flexibility in design, allowing products to be realized quickly with minimal waste (Kunovjanek et al., 2022).

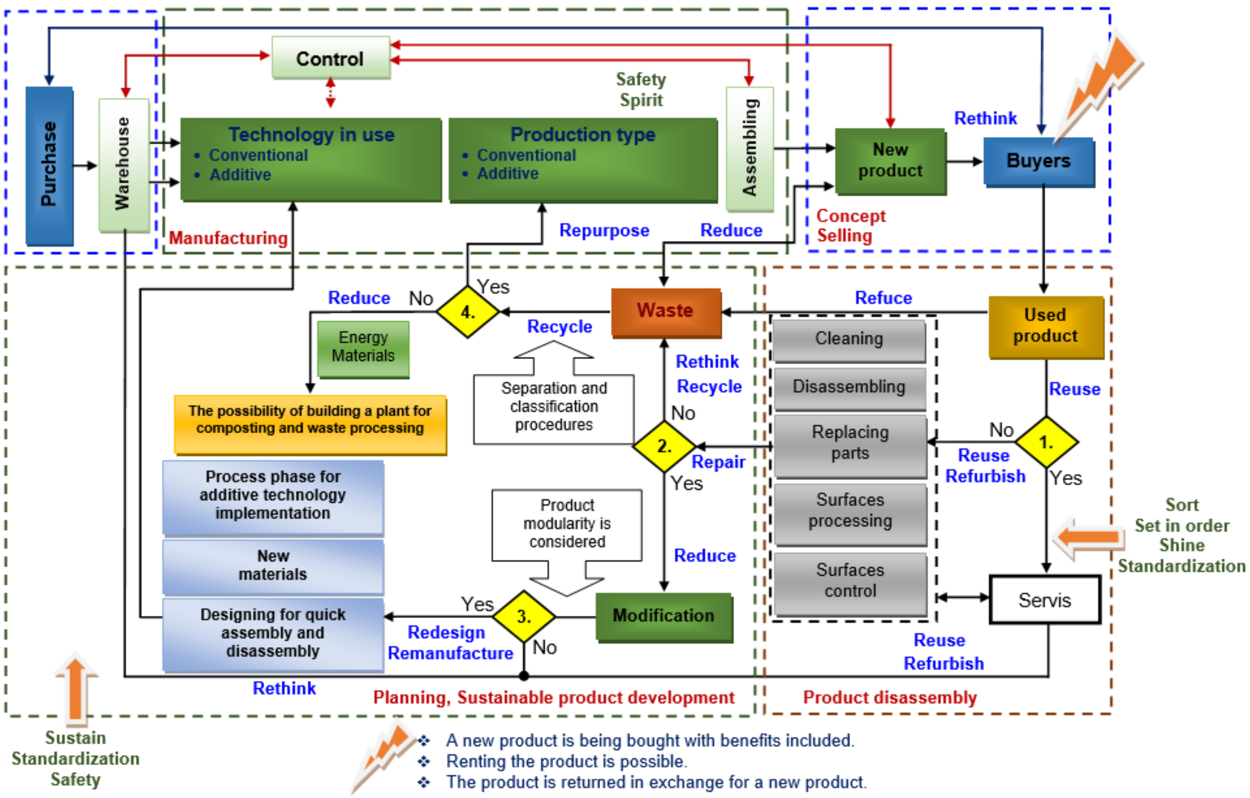


Figure 1: The position of concepts in product realization

An explanation of the workflow of activities in the advanced algorithm (Vorkapić et al., 2024), integrating the 10R circular economy (CE) strategy with the 7S tools of Lean production and wearable sensor lifecycle management, is provided in Table 4.

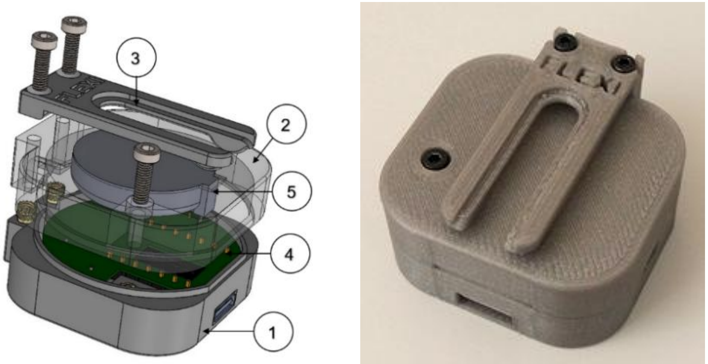
Table 4: Workflow of activities in product realization using CE

Flow	Decision	Question	Activity	S tool / R element
Purchase of products by users	Yes	Validation of correctness?	– Products are received. – Functional products are stored in a separate room. – Non-functional products are disassembled. – Raw materials and functional parts are sorted and categorized. – Waste that can be recycled is separated.	Sort Set in order Safety
				Refuse Reduce Reuse
Product functionality	Yes	Product functioning?	– A visual inspection is performed. – Functional parts are stored in the warehouse. – Parts that can be serviced are also stored for future use. – Regular workplace inspections are accomplished in conjunction with the routine maintenance of machines, tools, and equipment.	Shine Set in order Safety
				Reuse Refurbish
	No	Product not functioning?	– Non-functional products are disassembled. – Usable parts are disconnected, cleaned, and restored to functional condition. – Broken or damaged parts are disposed of as waste for later use.	Shine Set in order Safety
				Rethink Recycle
Component functionality	Yes	Components are tech correct.	– Cleaning, washing, polishing, painting, and replacing certain elements are achieved. – Organized and inspected elements are stored in the warehouse of functional parts for reuse. – Reuse of tools and equipment components is enabled.	Set in order Standardize Safety
				Reuse Repair
	No	Components are tech defective.	– Parts or components that are not used are disposed of as waste. – The sorting and classification of waste according to recyclability criteria need to be finalized.	Set in order Standardize Safety
				Reduce Recycle
Product modification	Yes	There is a need.	– Product modification is a strategic decision for enterprises focused on growth.	Set in order Standardize
				Reuse Remanufacture
	No	Without modification.	– The realised product is sent to the final goods warehouse.	Set in order Sustain Standardize
				Rethink
Waste minimization	Yes	Recycling possible.	– Enterprises have technology for waste processing that allows materials to be reused. – It is essential to standardize the workplace and provide employees with training and education.	Sustain Standardize
				Rethink Recycle
	No	Recycling is not possible.	– The enterprise utilizes outdated technologies that do not meet CE criteria. – A culture of CE-based thinking is encouraged.	Standardize Safety Spirit
				Reduce Recover

RESULTS

This work presents the realization of a wearable device for measuring body temperature. Using the presented algorithm, a methodological procedure for product realization is defined. Certain product elements were manufactured using. AM in accordance with the mentioned 7S tool and the 10R model within CE.

Before 3D printing, a 3D CAD model of the mentioned enclosure was created. The electronic enclosure assembly consists of: 1) the base, 2) the cover, and 3) the pressure element (clothespin). Inside the enclosure, there is: 4) electronics with Bluetooth communication, and 5) a battery to power the electronics; see Figure 2a. A prototype of the electronic enclosure for the body temperature measurement device is shown in Figure 2b.



a) b)

Figure 2: Electronic enclosure: a) Virtual model of the electronics enclosure, b) model produced by 3D printing

The virtual model shown in the figure is later transformed into a prototype using a 3D printer. At this stage, the designer can correct dimensions and modify the entire product design. The created CAD model is converted into an STL file, which is further processed. Preparation for printing is done using a specialized program, Prusa Slicer, which ultimately generates the G-code.

The prototype of the wearable temperature sensor device was produced on the Original Prusa MK3S+ printer. It is a mobile printer with a build volume of 250 x 210 x 210 mm, layer resolution of 0.05 - 0.3 mm (nozzle diameter), and printing speed of 10 - 100 mm/s. For the prototype, ZOTRAX PLA biodegradable filament with a diameter of 1.75 mm was used. This biodegradable material is made from environmentally friendly components. It has high hardness and very low shrinkage, making it popular for producing models that require a high level of precision and detail, especially for electronic enclosures. On the other hand, the chosen material is biodegradable and therefore eco-friendly.

During the 3D printing process, the designer must control the model manufacturing process, including material feed, heating and melting processes, and final print quality. All of this is acceptable if the prototype meets the criteria; if not, it is discarded as waste and later recycled for reuse. When removing support material, accuracy is carefully maintained to ensure precision. Removing support material requires a certain level of operator skill because mistakes can damage the produced elements. Excess material is collected in a separate recycling box according to the CE algorithm.

Inside the printed base of the wearable sensor casing, the electronics, including the remote temperature sensor and battery, are placed. Then the cover is installed, followed by the clip. Finally, all elements are fastened with M2.5 mm screws. The enclosures produced in this manner enable modification, quick disassembly, and upgrading with various sensor modules, thereby providing a range of different products. Additionally, if the device does not meet the end user's criteria, it can be reused, disassembled, or disposed of as recyclable waste. The assembled wearable device for measuring body temperature (as well as its setup) is shown in Figure 3.

Figure 3: Realized a wearable device for measuring body temperature

Figure 4 illustrates the functional architecture of the wearable temperature-sensor system within the Circular Economy (CE) framework (Li et al., 2021; Manas et al., 2029; Verma et al., 2025). The diagram integrates three essential subsystems: the sensing layer, the communication and processing layer, and the power-management layer. The sensing layer contains a temperature sensor that continuously monitors the user's skin temperature and transmits data to the microcontroller unit (MCU). The processing layer performs signal conditioning, filtering, and Bluetooth Low Energy (BLE) communication toward a mobile or cloud interface for data storage and visualization. The power-management block ensures energy efficiency through optimized charge–discharge cycles of a rechargeable battery, consistent with CE principles of *Reduce* and *Rethink*.

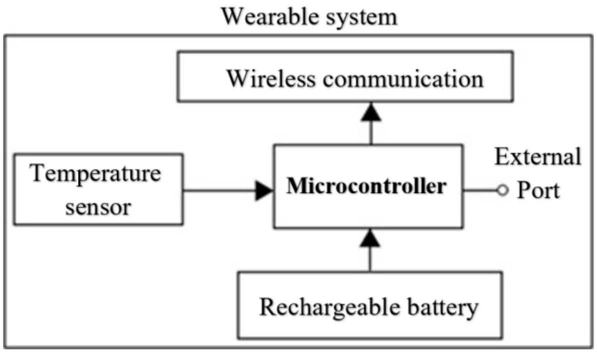


Figure 4: Block diagram of presented wearable system for measuring body temperature

From the perspective of the 10R strategy, each subsystem is designed for easy *Reuse*, *Repair*, and *Refurbishment*. Electronic components and the biodegradable enclosure can be separated for recycling (*Recycle*) or upgraded (*Remanufacture*), enabling multiple product life cycles. In accordance with the 7S tool, the system architecture supports *Standardization* and *Safety*, ensuring that assembly, testing, and maintenance operations are orderly, traceable, and ergonomic.

An additional external interface (port) further reinforces CE principles by allowing battery recharging and facilitating sustainable use through modular upgrades. This interface enables firmware updates and software improvements during the product's operational life, calibration of newly integrated temperature sensors, and diagnostic testing of the electronic circuit or battery condition. Such expandability prolongs product longevity and reduces electronic waste by enabling continuous performance enhancement without the need for full device replacement.

Consequently, the block diagram not only represents the data-flow logic of the wearable device but also embodies the closed-loop logic of sustainable product realization, integrating resource optimization, reuse, and long-term maintainability. In the realization of wearable sensors, the established algorithm is based on the activity flowchart used to initiate the manufacturing process of wearable sensors. The procedure for applying the CE strategy in the manufacturing of wearable sensor devices is outlined in Table 5.

According to Minunoo et al. (2018), disassemblability guides the process of taking separated products without the use of excessive tools and without engaging in unnecessary or undefined activities. Representative examples include the automotive and electronics industries, where standardization operates as a facilitating factor in disassembly (Langerak, 1997).

In the implementation of wearable sensors, the algorithm is based on the methodologies used to optimize the manufacturing process and the design process. In this regard, the 10R algorithm in the production of wearable sensors focuses on the following activities:

- Market analysis and user/customer requirements;
- Requirements that the wearable sensor should satisfy;
- Resource availability - materials, technologies, and personnel;
- Designing wearable sensors for multiple lifecycles;
- Manufacturing, testing, and evaluating functional prototypes;
- Closed-loop manufacturing using recycled materials; and
- Analyzing user feedback to improve future models and processes.

Table 5: The procedure for manufacturing of wearable sensor devices

No.	Activity	Importance
1.	Product reception.	Incentives are offered to customers when they return old products and buy new ones.
2.	Work order initiation.	The procurement, reception, and warehouse department activate a work order for the production department.
3.	Is the product functional?	Functional products are placed in the finished goods warehouse.
4.	Product disassembly.	The functionality of components and assemblies is tested.
5.	Can certain parts be reused?	Functional parts are cleaned (or repaired) and then stored in the warehouse for finished parts or semi-finished products.
6.	Component replacement.	Defective parts are replaced with new or modified components. Non-functional parts are disposed of as waste.
7.	Component modification.	For component modification, the additive manufacturing process is initiated.
8.	Initiation of additive manufacturing.	Various components are produced to save material and manufacturing time, maximizing material efficiency.
9.	Use of components from warehouse.	Repaired or new elements (produced conventionally) are retrieved from storage, as well as components made using additive manufacturing technologies.
10.	Inspection of finished parts.	All components are inspected, both those made through conventional processing and those produced using additive technologies.
11.	Product parts assembling.	The assembly process is carried out in the workshop, with strict attention to the order of operations.
12.	Product testing.	The functionality of the product and its specified parameters are tested in accordance with its intended purpose.
13.	Product completion.	Various materials play a crucial role in packaging, and additive technology also holds significant importance.
14.	Product packaging and documentation archiving.	Accompanying documentation and an invoice are issued with the product. The sales department is responsible for delivering finished or new products to customers.

DISCUSSION

The advantages of the 10R/7S algorithm, as illustrated in the example of wearable sensors within the Circular Economy (CE) concept, are reflected in the application of various solutions. The continuous development of new materials accompanies this process. It is estimated that by 2030, around 65% of the world's population will be using some form of wearable device, with the wearable device market expected to grow exponentially.

However, this also brings specific challenges, such as the need for regulation (specific standards and approvals by health organizations are required); inequality in access (socioeconomic status is a limiting factor); and user fatigue (concerns arising from constant use and health monitoring).

The use of bioplastics and thermoplastics is expected to reduce the consumption of natural resources. Wearable devices/sensors will play a key role in everyday life. There is a growing trend of miniaturizing sensor elements and electronic components.

Additive manufacturing (AM) is becoming a mighty factor in production, as it plays a crucial role in energy savings, enables shorter supply chains, and reduces overall production costs. Users of wearable sensors are empowered to participate in implementing the model.

The algorithm enables more effective market positioning for enterprises and enhances their competitiveness. It is necessary to respect and implement all elements of the 7S tool. It also significantly considers the reuse of devices through return programs and provides enterprises with appropriate compensation. Therefore, waste should be significantly reduced.

The described 10R/7S strategy for the sustainable development of wearable sensors provides a complete framework for how every enterprise should operate. By applying the 10R strategy within the Circular Economy (CE), enterprises could:

– Produce new products with minimal energy and material losses;
– Significantly reduce or eliminate environmentally harmful waste through the use of new technologies and biodegradable materials;
– Extend the product life cycle; and
– Shorten the time-to-market for new products.

The study demonstrates that it is possible to create a prototype from new biodegradable materials, implement rapid design modifications, and perform testing on an existing product. The enclosure for the electronic components is compact and small in size. It can be worn either on the head or around the waist of the user (a clip enables high maneuverability). In the development of wearable sensors, the assemblies must be modular, easy to disassemble, and made from biodegradable thermoplastic polymer materials, as well as from recyclable materials.

From an electronics perspective, the prototype demonstrates how a minimalist sensing chain (sensor → MCU → BLE → client app) can be architected for longevity and reuse. Each block was selected with modular substitution in mind: a pin-compatible temperature sensor can be swapped without altering the MCU firmware interface; the BLE-enabled MCU exposes well-defined services for data and maintenance; and the power path is partitioned so the battery subsystem can evolve independently. The external service port already proved valuable in practice, enabling battery recharging, firmware updates, calibration of replacement sensors, and fast diagnostics, thus directly supporting Repair, Refurbish, and Remanufacture within the 10R model.

Design-for-X (DfX) principles were intentionally embedded to support CE goals. Design-for-test (DfT) was addressed via clearly accessible pads (SWD/UART/I²C) and scripted production tests; Design-for-assembly (DfA) through simplified fasteners, connectorized subassemblies, and avoidance of permanent adhesives; and design-for-disassembly (DfD) via separable modules and recyclable housing. These choices reduce non-value-added time in production (7S: Set in order, Standardize), shorten service cycles in the field (7S: Shine, Sustain), and increase the viability of component harvesting at end-of-life (10R: Reuse/Recycle).

Electromagnetic compatibility (EMC) and reliability were considered as enablers of sustainability rather than afterthoughts. Proper grounding, short sensor traces, and decoupling reduce rework and warranty returns; conformal coating and strain-relief on flex points improve survivability under daily wear. Biocompatibility of skin-contact materials (housing, strap, adhesives) and ingress protection at the sensor window are likewise integral to lifecycle performance, lowering premature disposal and supporting extended reuse cycles.

Looking forward, the electronic design can be strengthened along four axes. Power: migrate to an ultra-low-Iq PMIC with coulomb counting, introduce hard power domains and aggressive sleep states, explore energy harvesting (body-heat TEG or motion-based), and add smart charging with thermistor-based safety. Sensing: support hot-swappable sensor mezzanines (I²C/SPI on a keyed micro-connector) so users can upgrade from a baseline temperature sensor to combined temperature-humidity or skin-thermistor/probe variants without replacing the main board. Compute/Connectivity: adopt MCUs with secure boot and hardware crypto for over-the-air updates, expand BLE profiles for interoperability, and optionally add on-device filtering/anomaly detection to reduce radio duty cycle. Maintainability: embed a self-test routine (sensor open/short detection, reference readback), on-device calibration constants with versioning, and a field-service dashboard accessible via the external port.

To deepen CE alignment, future revisions can implement a repairability index at the BOM/assembly level (screw count, tool class, spare availability), publish a service manual, and offer take-back with credit for core modules that pass incoming QA (10R: Return/Recover). Material passports for the PCB and enclosure—listing resin type, additives, and recycling pathways—will facilitate responsible end-of-life sorting. Moving to standardized fasteners and eliminating mixed polymers in single parts will further improve recyclability and reduce sorting losses.

Finally, data governance features should evolve in parallel with hardware. Secure key storage, encrypted links, and signed firmware protect patient data and device integrity; calibration audit trails and immutable logs (hash-chained records) strengthen traceability and compliance. Together with a modular electronics stack and a service-friendly enclosure, these measures close the loop between design, use, service, and recovery, translating the 10R strategy and 7S discipline into everyday engineering decisions that make wearable sensors both sustainable and resilient.

CONCLUSION

This work shows that applying the 10R/7S algorithm to wearable sensors yields a concrete, end-to-end pathway for Circular Economy implementation. By prioritizing bioplastics and thermoplastics, modular subassemblies, and design-for-disassembly, we demonstrate how new devices can be brought to market with lower material and energy demand, longer service life, and reduced waste. Additive manufacturing strengthens these outcomes by shortening supply chains and enabling rapid, low-overhead iteration, while structured reuse and return programs translate directly into component recovery and measurable waste reduction.

At the product level, the prototype validates how a minimalist sensing chain (sensor → MCU → BLE → client app) can be architected for longevity and serviceability. A clearly defined service interface enables recharging, firmware updates, calibration, and diagnostics, supporting repair, refurbishment, and remanufacture without replacing the main electronics. Intentional DfX choices—test, assembly, and disassembly—together with EMC/reliability practices and skin-contact material considerations, reduce rework and premature failures, thereby reinforcing Circular Economy performance in everyday operation.

The benefits of integrating the 10R circular economy (CE) strategy with the 7S tools of Lean manufacturing and life cycle management of wearable sensors are reflected in the implementation of various solutions. Estimates show that by 2030, about 65% of the world's population will use some form of wearable device, and the wearable device market is expected to grow exponentially. The first application of the algorithm was described in detail in previous research on the example of manufacturing a temperature transmitter housing (Vorkapić & Ivanov, 2022). However, the algorithm also brings specific challenges, such as the need for regulation (specific standards and approvals from health organizations are needed); unequal access (socioeconomic status is a limiting factor); and user fatigue (problems arising from constant use and health monitoring). The increased use of bioplastics and thermoplastics is expected to reduce the consumption of natural resources. Wearable devices/sensors will play a key role in everyday life. There is a growing trend of miniaturization of sensor elements and electronic components. On the other hand, AM is becoming a strong factor in production, as it plays a key role in energy savings, enables shorter supply chains and reduces overall production costs.

Users of wearable sensors become empowered participants in the implementation of the model. From a strategic perspective, it is a very important aspect of positioning companies in the market and increasing their competitiveness. Therefore, it is necessary to implement all 10R principles through the involvement of 7S tools. Reusing wearable devices through return programs would provide companies with appropriate compensation. The application of the 10R strategy within CE allows companies to:

- produce new products with minimal energy and material losses;
- significantly reduce or eliminate environmentally harmful waste through the use of new technologies and biodegradable materials;
- extend the life of the product; and
- shorten the time needed to place new products on the market.

The manuscript demonstrates that it is possible to form a prototype using new biodegradable materials, support immediate design modifications, and complete testing on an existing product. The enclosure for the electronic components is user-friendly and compact, allowing it to be worn on the head or around the waist for high maneuverability. In developing wearable sensors, assemblies must remain modular and easy to disassemble.

Wearable sensors have certain methodological limitations. The precision of the collected data may vary depending on the type of sensor, how it is worn, the user's individual characteristics, and environmental conditions, leading to systematic deviations. In addition, most analyses rely on limited or specific population samples, so the findings cannot always be directly generalized to the broader population or to different application contexts. Therefore, it is necessary to analyze the results with notification and clearly define the framework in which they are valid.

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PRIMENA 10R STRATEGIJE I 7S ALATA U RAZVOJU NOSIVIH SENZORA

Rad prikazuje integraciju 10R strategije cirkularne ekonomije (CE) sa 7S alatima vitke (Lean) proizvodnje i upravljanja životnim ciklusom nosivih senzora. Predstavljeni algoritam, zasnovan na CE principima, i primena aditivne proizvodnje (AP) u realizaciji modularnog kućišta od biorazgradivog polimernog materijala, demonstriraju strategiju održivog razvoja prototipova sa minimalnim otpadom materijala, mogućnošću brzih promena dizajna, jednostavnom rastavljivošću i sklapanjem, kao i ponovnom upotrebom, popravkom i revitalizacijom. Navedeni algoritam zatvara krug između dizajna, upotrebe, održavanja i kraja životnog veka proizvoda, uključujući održivost u svakodnevne inženjerske odluke kroz primer nosivih senzora. Prikazano elektronsko kućište je kompaktno; može se nositi oko struka ili fiksirati na glavu pomoću fleksibilnog kaiša. Rezultati su pokazali da povezivanje 10R i 7S povećava konkurentnost preduzeća kroz efikasnu proizvodnju, produžen vek trajanja proizvoda i smanjenje otpada, istovremeno odgovarajući na izazove kao što su poštovanje regulative, pristupačnost i povratne informacije korisnika nakon dugotrajne upotrebe proizvoda. Studija potvrđuje praktičnu metodologiju primene principa cirkularne ekonomije na sisteme nosivih senzora i ističe mogućnosti za modularna poboljšanja, servisibilnost i upotrebu ekološki prihvatljivih materijala. Rad doprinosi oblasti inženjeringa i dizajna proizvoda prikupljanjem saznanja o održivom razvoju proizvoda i efikasnijem upravljanju njihovim životnim ciklusom.

Ključne reči: 10R strategija; 7S alati; Cirkularna ekonomija; Aditivne tehnologije; Nosivi senzori; Telesna temperatura.