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ADDITIVE TECHNOLOGY AND 7R METHODOLOGY IN CIRCULAR ECONOMY FOR WEARABLE SENSORS PRODUCTION

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Original Scientific Paper

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The paper presents the 7R algorithm of the circular economy principle in realizing wearable sensors. The application of additive manufacturing in the realization of sensors is essential from the point of view of sustainable production, which starts from the material and ends with its recycling process. All seven principles and their connection with additive manufacturing as a critical element in the circular economy are presented. The paper defines the theoretical framework for realizing a sustainable wearable sensor. The production of such sensors primarily refers to the application of flexible 3D printing and electronic components that can be quickly replaced, modified, disassembled, and recycled.

Keywords: Wearable sensors; 7R model; Additive manufacturing; Algorithm; Circular economy.

INTRODUCTION

Sustainable enterprise development includes additive technology through rational use of resources, application of flexible production systems, use of new materials (mainly non-metallic), and adoption of new business models (Despeisse & Ford, 2015). The application of additive technology creates additional value in the realization of products compared to conventional processing methods.

The circular economy (CE) represents an economic model that is designed to minimize waste while maximizing the use of available resources (Velenturf & Purnell, 2021). It is based on the 7R model. The essential elements of the 7R model are redesign, refuse, reduce, reuse, repair, recycle, and recover.

Through the 7R model, CE strives to use material resources better. The 7R model is an extension of the traditional 6R model (Dung & Hong, 2021); it provides an essential framework for adopting the basic principles of CE in different product life cycle phases. The last "R" stands for "Recovery," which emphasizes the importance of restoring materials and different phases of the product's life cycle (Lewandowski, 2016). An explanation of all 7R elements is given in Table 1.

Remanufacturing is a production process within CE. Remanufacturing is considered an appropriate solution for the enterprise's sustainable development because it affects not only the

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reduction of waste but also the reduction of the impact on the environment and the conservation of energy. Remanufacturing involves using recycled products to reduce costs, thus increasing profits and improving stability in investments (Gehin et al., 2008).

Table 1: 7R model

R	Meaning
Redesign	– Redesign primarily refers to rethinking product design, manufacturing, and consumption. The redesign makes sense if there are strong links between design, manufacturing processes, and material selection.
Reduce	– Product refuse is considered when products are not sustainable, and customers are suggested to avoid such products.
Reduce	– Waste reduction indicates the need to reduce or minimize waste. It also minimizes the use of natural resources and new materials and resources during the design and manufacturing process.
Reuse	– Reusing the products or components is essential to extend the product life cycle. It includes designing easily serviced, repaired, refurbished, and reused products. When designing, "design for disassembly and reassembly" is exciting, that is, how to design a product where parts can be easily separated and reassembled while reusing materials and specific components (Bocken et al., 2016; Despeisse et al., 2017). Designers should design the product for multiple life cycles (Andrews, 2015).
Repair	– Product repair means returning the product to its correct condition after being rejected, alienated, or damaged. Products are designed to be easily repaired to extend the life of their circle.
Recycle	– Recycling is the recovery of materials from products at the end of their life. It involves processing used materials to create new products, reducing the demand for natural resources, and reducing waste to a minimum. Plastic recycling is a way to reduce the accumulation of plastic material due to daily use, mainly due to the hyperproduction of packaging.
Recover	– It means, energy or materials recovery from waste that cannot be recycled. It may involve recovering energy through incineration or extracting valuable materials from non-recyclable waste (Van Caneghem et al., 2019).

New technologies and materials are used, and the total mass and product volume is reduced; that is, the design and functionality of the product are improved (Diegel et al., 2020). From an economic point of view, remanufacturing offers a compromise solution related to minimizing total costs in the new product realization (Cesur et al., 2020). In that case, the 7R model is fully incorporated into the remanufacturing process.

Additive manufacturing and CE concept

Additive manufacturing (AM) contributes to improving resource efficiency and operational efficiency, functionality, and durability. On the other hand, it enables reuse, repair, and product recycling at the end of the life cycle (Despeisse & Ford, 2015; Gupta et al., 2012). AM reduces the total mass and excessive use of water, energy, and materials, indicating that it complies with CE goals (Holmström et al., 2010), see Table 2.

Additive manufacturing and wearable sensors

Textiles can be natural or synthetic. Natural textiles (cotton and silk fibres) offer excellent moisture absorption, softness, and elasticity in clinging to the body and acceptable breathability. Synthetic textiles are synthetic fibres, including nylon, polyester, and acrylic. These materials absorb moisture well and have good durability, strength, and conductivity (Wang et al., 2016).

Generally, wearable sensors are divided into strain, pressure, temperature, and humidity sensors. Functionally, each sensor element converts input signals into electrical signals. The materials of conventional sensor elements are generally not rigid or flexible, which limits their use. That is why the realization of flexible load-bearing structures, which primarily include stretchable thermoreactive and thermoplastic polymers, is being pursued (Osman & Lu, 2023).

Wearable sensors (often called biosensors) on textiles cover control, prevention, and health protection. They detect movements and measure pulse, blood pressure, body temperature, body movements, and sweating. Today, wearable sensors are entirely flexible and different from the traditional ones based on silicon (Li et al., 2023). The presence of wearable sensors becomes very important in health care, monitoring, and treatment of various ailments and diseases. Progress is certainly being made in the flexible electronic realization that sticks firmly to the human body. This concept represents a noninvasive method, where the onset or predisposition to the disease can be predicted with great reliability. Flexible sensors are easily adapted to the human skin, so unobstructed and fast signal collection from the human body is possible (Xu et al., 2019).

Table 2: Importance of AM in the CE concept

Process	Importance	Goal
Production launching	– The need for large-scale and mass production is reduced.	– Overproduction is minimized.
Resource usage	– AM does not result in material loss.	– The material in the process is minimized, which leads to a waste reduction.
Products adaptation	– AM facilitates rapid product adaptation to market needs. The likelihood of products becoming obsolete or discarded is reduced.	– The possibility of producing the same or outdated products is minimized. Products are designed for multiple life cycles.
Product repair and maintenance	– AM has a role in replacing worn-out or defective (non-functional) parts. It allows a defective (or damaged) part to be replaced immediately.	– The possibility of the product being rejected is minimized, whether it is a malfunction or a minor defect. AM contributes to replacing defective components and reusing the product.
Closed-loop system	– AM can be integrated into closed-loop systems where end-of-life products are recycled into 3D printing feedstock.	– A circular flow of materials is created, including original resources with minimal use of new ones.
Localized production	– AM takes place in one location. The supply chain is shrinking.	– Minimizes the supply chain and thus the emission of the carbon footprint.
Prototyping	– Rapid prototyping allows designers to iterate and test concepts quickly.	– Prototyping time is minimized. An optimal and sustainable design is obtained before series and mass production.
Materials recycling	– AM allows the usage of recycled or biodegradable materials.	– The production process sustainability is greatly improved.
Waste reduction	– AM enables product realization with "layer by layer" technology. In this process, the required amount of material is used without waste.	– Waste is minimized during the product realization.

The advantages of using wearable sensors are reflected in the direct printing of flexible electronics on textiles or the usage of AM to make various electronic enclosers. AM offers many advantages over traditional manufacturing, including more design freedom, low-cost manufacturing, high automation, and short manufacturing cycle times (Ngo et al., 2018):

AM plays a vital role in wearable sensor designing and manufacturing, and AM is defined by the following parameters (Kalkal et al., 2021; Mukhopadhyay et al., 2022; Padash et al., 2020).

1. Design specificity – Complex models must be adapted to a specific purpose. Wearable environmental sensors are designed for clothing or particular body parts, providing comfort and functionality.
2. Structure simplicity - AM enables the creation of light and complex structures. Realized models should be comfortable and not interfere with daily activities.
3. Integration with clothing—Sensors can be integrated into clothing. Wearable environmental sensors can be embedded in fabrics or attached to clothing items, enabling unobstructed and unobtrusive monitoring of parameters.

4. Prototyping through multiple iterations - Fast prototyping enables the realization of numerous variants depending on where the sensor will be placed. It allows the designer to iterate and test different prototypes of wearable sensors quickly.
5. Components flexibility - Today, AM allows the incorporation of flexible materials to create flexible sensor components that can adapt to the body's shape.
6. Sensor housing - Realizing the housing for wearable sensors implies an elegant, compact, and ergonomically functional design.
7. Material in use - AM allows using a wide range of materials. These materials can be combined with fabrics to form lightweight, flexible, and convenient wearable sensor applications.
8. Open design and innovation - Open design encourages innovation and collaboration. Printed wearable sensors can be shared, modified, or improved within the community of manufacturers and researchers. This affordability encourages individuals to design and implement wearable sensors to collect environmental data.

RESEARCH METHODOLOGY

This paper aims to define 7R elements for the sustainable development of companies in a circular economy. AM uses a 7R algorithm to implement new or used elements/parts for the organization's sustainable development, see Figure 1 (Vorkapić & Ivanov, 2022). Also, in the sustainable development process, this model has about 80% positive impact on the environment (Diaz et al., 2021).

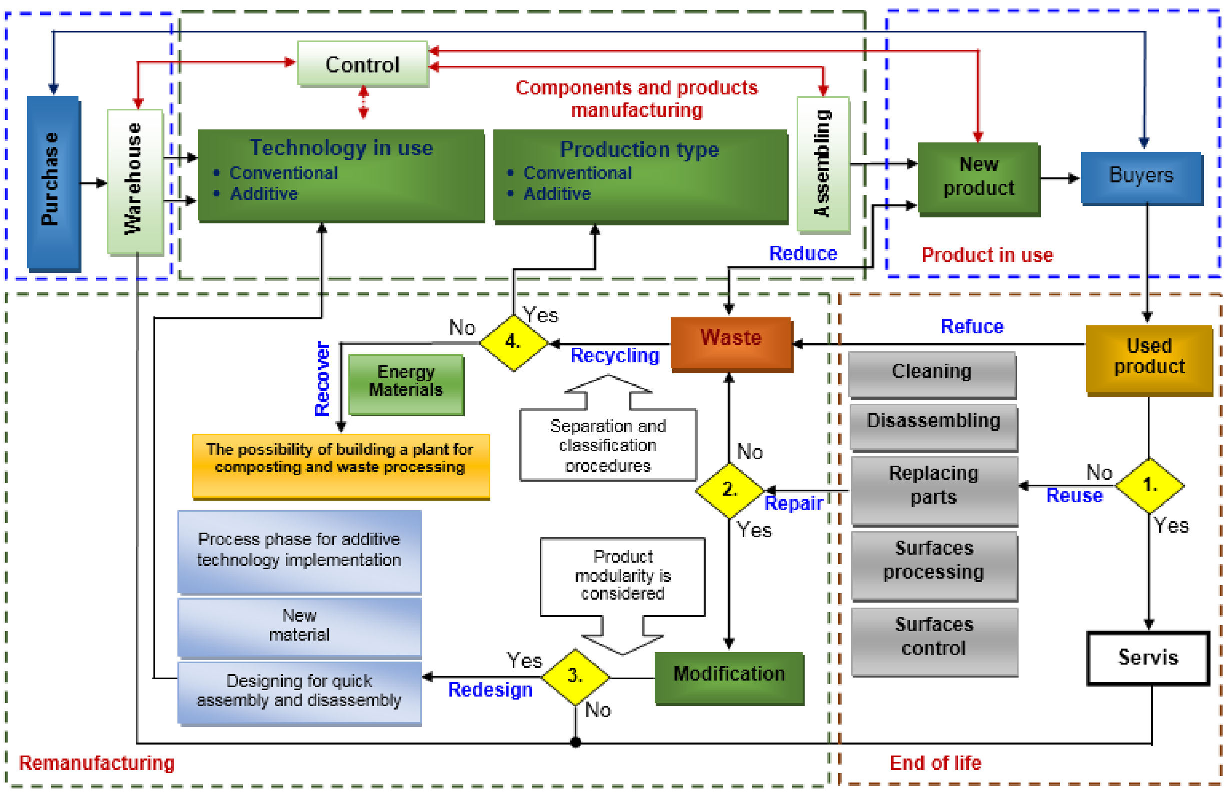

Figure 1: CE and 7R algorithm in wearable sensor production

Through the 7R model, the CE concept in the enterprise's sustainable development creates a solid connection between the seller and the buyer. Figure 1 gives the algorithm for applying the 7R model through the implementation of AM in the realization of new/modified or redesigned existing elements. In the algorithm realization, numerous literature sources and their solutions were used (Lahrour & Brissaud, 2018; Sartal et al., 2020). In the algorithm, remanufacturing is included in a closed loop during the realization of the plastic model and the conversion of plastic waste into filament (Shanmugam et al., 2020). Customers influence product redesign. Compromise solutions are given there, or customer suggestions are adopted to reach acceptable solutions regarding product realization (Risdiyono & Koomsap, 2013).

Before starting AM, the parameters are defined, and the material is selected. Model shape and required equipment size also dictate the production flow for cost and productivity reasons. Print control must be carried out during the model-making process, including material flow, heating and melting of the material, and print quality. At the end of the production process, additional control of the geometry and surfaces is performed during the realization of the model. Finally, the accepted model is further refined (mechanically and chemically).

The product comprises completely new, refreshed (repaired), and modified parts. Of course, there is also a combination of the mentioned components/assemblies. If the product is purchased from the user, it is checked immediately upon receipt. It states that the product is working (correct, meaning it can still be used) or not (defective/out of use), as shown in the algorithm (Fig. 1). In the algorithm, the main guidelines for the application of the 7R model in the sustainable development of the company are given. In this regard, the following questions are asked (Matsumoto et al., 2016):

1. Product correctness? (1). If the product is in function or within the warranty period - (the answer YES), a visual inspection and servicing of the product is carried out. Servicing means disassembling the product, cleaning, checking the correctness of the disassembled components, and repairing or replacing them with new ones. However, when disassembling the product, a high degree of uncertainty can occur due to the modification or realization of a new product using AM. Correct parts are stored in the warehouse. The product is disassembled when defective (the answer is NO). Usable parts are taken, and with specific technological processing and finishing, they are returned to a state of usability. The disassembly of used products provides the necessary raw material; that is, the process refers to the primary setting of the circular economy through the achievement of sustainable industrial development. On the other hand, disassembly contributes to accelerating the waste recycling process (Mao et al., 2021).
2. Components degree of usability? (2). Components/parts not used are disposed of in the waste (answer NO). If some components are technically correct (answer YES), technological operations such as washing, cleaning, sandblasting, polishing, chemical treatment, lubrication, and replacing certain elements are performed. After treatment, the repaired elements are deposited in the warehouse of (correct) parts for reuse. Therefore, when designing a product, one should consider quick replaceability, disassembly, and the possibility of finishing and reusing components/ assemblies.
3. Product modification? (3). If the product is not modified, then the answer is NO; that is, it goes to the warehouse of finished products. If the enterprise is strategically oriented, product modification is a good decision (then the answer is YES).
4. Waste recycling? (4). The algorithm considers waste as an essential resource. If the product cannot be recycled (answer NO), the enterprise has outdated technologies and must comply with the CE objectives. If recycling is possible (answer YES), enterprises have the technology to process waste for reuse. In this case, AM allows using recycled waste, which reduces the need to make parts conventionally.

According to the presented algorithm, the 7R concept in wearable sensor production takes place through the following stages (Perez & Zeadally, 2021; Vivaldi et al., 2022):

1. Designing wearable sensors for multiple life cycles - Implies the realization of modular and upgradable sensors where individual components or assemblies can be replaced or upgraded without discarding the entire device.
2. Material selection - Here, it is essential to choose materials that have as little impact on the environment as possible. Preferably, these are materials that can be recycled or reused.
3. Resource availability - Using resources during production means reducing material waste. Here, the use of additive technology is specifically considered.
4. Closed type production. - This type of production implies the use and reuse of recycled materials. As for the sensors, they are disassembled, reprocessed, or recycled at the end of their life.
5. Energy efficiency - The designed sensors should be energy-efficient.

DISCUSSION AND CONCLUSION

The presented analysis demonstrated that AM has an overall role in various applications regarding the concept of CE. There are still great difficulties when it comes to plastic recycling and its reaffirmation in the framework of sustainable development. Problems also arise at the level of product design because biocompatible and biodegradable plastic is imperative when it comes to wearable sensors. New materials that are more suitable for recycling are still being developed.

Wearable sensors have numerous applications in various fields, offering valuable insight into human health, from vital life signs and chronic disease management to physical activity monitoring. In the future, wearable sensors will play an essential role in everyday life. The trend of miniaturizing packaging design and improved measuring precision with multiple parameters will continue. Wearable sensors will also help monitor environmental factors, such as air quality, pollution levels, and exposure to UV radiation. There are exciting achievements in the field of flexible materials for wearable sensors that include the development of flexible materials as well as the application of biodegradable materials (Liu et al., 2022).

Today, wearable sensors in fashion design represent a synergy of technology, innovation, and innovativeness. The algorithm of application of AM and 7R models in the sustainable development of enterprises through CE gives the user of the product more possibilities. AM enables the rapid realization of wearable sensors while waste is considered usable.

The 7R model realization in the production and application of wearable sensors has its scientific research and economic justification. The scientific and research justification is reflected in the application of AM, which is becoming an increasingly important and effective tool when dealing with specific and sophisticated products. This manufacturing process is significant in terms of energy consumption, shorter supply chains, reduced costs, and shorter production times.

Economic justification is reflected in the implementation of sustainable production to reduce environmental pollution, the use of non-renewable resources, and the accumulation of waste. According to CE requirements, the AM should produce less material waste and contribute to reduced carbon dioxide emissions.

Reusing obsolete products becomes a strategic decision, an element of the enterprise's business excellence. However, despite the advantages of algorithms for enterprises, there are still obstacles to accepting the CE concept, which is reflected in poorly developed research and development activities and the inability to respond to market demands quickly.

In this direction, the connections between organizational cultures and the product development process should be harmonized. Sustainable product development implies design, parameters optimization, implementation, exploitation, and further product improvement from the perspective of the 7R model within the circular economy.

The quality of wearable sensors should be related to reliability, the ability to constantly upgrade, compatibility, quick disassembly and repair, and recycling of individual elements (George et al., 2023). Wearable sensor manufacturing means no production with dangerous components harmful to the environment. Also, it means a longer product life cycle through permanent modification and constant improvement by applying new technologies, where additive technology stands out in the foreground.

FDM printing has revolutionized the way people approach design and manufacturing. With FDM printers becoming more affordable and accessible, users have the power to create customized objects for their specific needs right from the comfort of their homes or workplaces. The benefit of FDM printing is its versatility. Users can design and manufacture various objects, from simple electronic prototypes to complex mechanical parts, artistic creations, household items, and as well as prosthetics.

The paper presents the algorithm and procedures for introducing the 7R strategy in sustainable enterprise development. The algorithm introduces AM to improve manufacturing through the fast realization of models/prototypes, communication with customers, and quick reactions on the market. Waste (and its reuse) is presented as an essential resource. Reusing obsolete products with redesign and remanufacturing gives a particular focus on the enterprise's business excellence in manufacturing sensors.

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ADITIVNA TEHNOLOGIJA I METODOLOGIJA 7R U CIRCULARNOJ EKONOMICI ZA PROIZVODNJU NOSIVIH SENZORA

U radu je prikazan algoritam 7R principa cirkularne ekonomije u realizaciji nosivih senzora. Primena aditivne proizvodnje u realizaciji senzora važna je sa stanovišta održive proizvodnje koji kreće od materijala, a završava se postupkom njegove reciklaže. Prikazano je svih sedam principa i njihova veza sa aditivnom proizvodnjom kao ključnim elementom u cirkularnoj ekonomiji. U radu su definisani teorijski okviri za realizaciju održivog nosivog senzora. Izrada takvog senzora se prevashodno odnosi na primenu fleksibilne 3D štampe i elektronskih komponentni koji mogu da se brzo zamene, modifikuju, dorade, rastave i recikliraju.

Ključne reči: Nosivi senzori; 7R model; Aditivna proizvodnja; Algoritam; Cirkularna ekonomija.