

Smart Textiles: Enhancing Digital Transformation in Healthcare through Circular Economy Principles

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Abstract

This paper investigates the intersection of smart textiles, circular economy principles, and digital transformation, with a specific focus on their applications in the healthcare industry. Smart textiles offer immense potential in healthcare, enabling vital signs monitoring and measurement in both home and hospital care settings. However, their development necessitates considerations of longevity, durability, reparability, and environmentally-friendly disposal, aligning with circular economy principles and sustainability goals. This research conducts a comprehensive literature review, analyzing the interconnection between the circular economy, smart textiles, and digital transformation. The review synthesizes relevant literature to identify key findings and insights, highlighting the current state of research in this interdisciplinary domain. Moreover, the paper assesses the implications and potential impacts that arise when combining these three domains into a unified framework. By exploring the interplay between smart textiles, circular economy principles, and digital transformation, this study contributes to a deeper understanding of how these domains can be effectively integrated to drive innovation in the healthcare sector.

Keywords

Digital Transformation, Smart Textiles, Circular Economy, Reusability, Healthcare.

1. Introduction and Motivation

Digital transformation in healthcare is currently the subject of much research, but also of European strategies and policies. The process of digital transformation encompasses a wide range of areas, technologies and processes that are related to the delivery of care. The aim is to ensure the efficiency, accessibility and safety of the entire healthcare system. In this paper, we look in more detail at technologies that enable the acquisition of patient data using sensors that are part of so-called smart garments. And it is important to recognize the importance of this data in the whole process of digitalization.

The new field of smart textiles is getting more and more attention, given the technological advances that have been quite visible in recent years. The smart textiles market is estimated to be valued at 2.3 billion in 2021. It is estimated that around 2026 this market will reach a value of 6.6 billion due to the significant growth that has occurred in recent years (Collective 2022). By smart textiles, we can think of value-added textiles, which can be added functionality in the form of electronic components that can add another level of healthcare delivery, for example, in the healthcare sector. In the case of smart textiles, the focus should be on how they are produced and the materials used to ensure reusability and avoid unnecessary waste. This opens up a lot of scope for manufacturing with high-quality and durable materials (Mečňika and Dipl 2014). The circular economy is currently a highly debated topic. This is the name for a

closed-loop economic system. The idea behind this concept is that raw materials, components, and products lose as little value as possible and can circulate. (“What Is the Definition of a Circular Economy?,” n.d.).

Today, the European Commission adopted a new Circular Economy Action Plan - one of the main building blocks of the European Green Deal, Europe's new agenda for sustainable growth. With measures along the entire life cycle of products, the new Action Plan aims to make our economy fit for a green future, strengthen our competitiveness while protecting the environment and give new rights to consumers. In healthcare, the implementation of circular economy principles is an interesting topic, as the experience of managing the COVID-19 pandemic in the context of increasing amounts of protective equipment waste shows.

Our research aims to identify opportunities for the implementation of smart textiles for healthcare applications with an aim to make healthcare more efficient while taking into account the requirements of the Circular Economy and the digital transformation of healthcare.

2. Literature Review

2.1. Digital Transformation and Healthcare

The topic of digital transformation in healthcare has been presented in various papers, for example (Kazançoğlu et al. 2021). Two important concepts appear in this article, one is smart textiles, and the other is the circular economy. These words were key to the data collection, but the main objective was to find out how these two concepts are related and what research can currently be traced on their intersection.

Digital transformation in healthcare is currently the subject of research and publications by many research teams. For example, the article (Kraus et al. 2021) presents a systematic literature review on the current state of digital transformation in healthcare. It is also a field that involves different technologies that are integrated with each other. These technologies should help in particular in the context of communication between patient and doctor and between doctors themselves, including other stakeholders such as health insurers and healthcare organizations.

These technologies have applications not only in acute care but also in preventive and follow-up care, including in the social field. Specifically, the individual authors describe the following technologies, for example:

- Telemedicine
- Big data
- IoT
- Virtual Reality
- AI
- 3d printing

The basic prerequisite for digital transformation is the creation of a digital model that contains processes and their links in the context of stakeholder needs. Basic business process analysis and modelling tools can be used to create such a digital model. It is important in this process to identify not only the individual activities but also the data and how they are processed. This data must also be viewed from the perspective of its security, i.e. availability and integrity.

In specific, data on individual patients that indicate their health status are key. In acute and intensive care, this data is obtained through monitoring and continuous monitoring using various probes, catheters, etc. The question is, therefore how to monitor the patient in the context of preventive or post-acute care, where the connection of the patient to the devices is more complex. Therefore, one promising area is the use of smart textiles that can be fitted with sensors to monitor selected patient functions.

Research into the use of these textiles also needs to look at the issue of their production and recycling in the context of the requirements of the principles of the circular economy. Introducing the concept of the circular economy into production is now a requirement that stems from European policies aimed at the Green Deal.

Therefore, this paper will further focus on the area of smart textiles in the context of the requirements of the circular economy in the healthcare sector.

2.2 Circular Economy

Although the article (Siderius and Poldner 2021) deals with an interesting topic, there is a very important term for the concept of the circular economy. It is called the Circular Business Model. It is a model through which companies create value along the value chain, contributing to a longer product life cycle (Siderius and Poldner 2021). Another article reviews existing literature on this topic, divided into different areas. The first area of focus is about roots and origins of the circular economy.

The second area is about Circular Economy principles and limits. A few of the articles in the review form a third area which is about Circular Economy Models. Then the work splits into three areas of implementation at the micro (single company or consumer), micro (eco-industrial park) and macro level (city, province, region, nation). Implementation at the micro level consists of cleaner production, green consumption and green public procurement, product recycling and reuse, scavengers and decomposers and policy. On the micro level, there are areas of Eco-industrial systems and industrial symbiosis districts and networks, waste trade markets and policy. The last area is implementation at the macro level, and its areas are regional eco-industrial networks and productions, eco-cities, urban symbiosis, collaborative consumption, zero waste programs, innovative municipal solid waste management systems and policy. Then separate from other areas are indicators and decoupling (Ghisellini, Cialani, and Ulgiati 2016).

A very important view on why the textile industry needs change is in the article (EMF 2017). There they are addressing the issue of the whole textile industry. It is worth noting that over time, sales will grow, and this will increase the number of textiles in circulation. In contrast, the use of clothing, i.e. the number of times it has been worn before it is no longer used, gradually decreases over time. This gradually brings us to a point where the supply of new clothing products exceeds the number of clothes that are not used. (EMF 2017) This shows that the potential of the circular economy in the textile industry is huge.

Another important part of the literature search is a review article that deals with the topic of end-of-life products. Here the authors divide the available articles from 2005 to 2020 into Smart Textile Services, Designing an eco-friendly strategy and Education, Guidelines. The most important of these is the area of eco-friendly strategy. Here it is stated that to create a recyclable product, this needs to be considered at the product design stage. At this stage, it is important to consider the environmental impacts throughout the life of the product. Recyclability is one of the big challenges as it is a very complex issue, for example, papers (Esbeih et al. 2021) or (Ashour 2021).

The applications of e-textiles are wide-ranging, and hence recyclability is dependent on the area of application of the e-textile. (Veske and Ilén 2021) The most recent article in this category that has been selected for further exploration is the article. (Wu and Devendorf 2020) This article deals with the design of smart textiles for their disassembly and reuse of materials. The main objective of the paper is to show how computer-aided design can link developments in areas such as craft, textile engineering, and material science to advanced sustainability. The life cycle of smart textiles that are designed for disassembly is proposed (Wu and Devendorf 2020). This article presents the content of the workshop, where the aim was to show the process of disassembling e-textiles, what they contain, the different lifetimes of textiles and, electronics and other components.

There is an attempt to generate discussion on topics such as methods for extending product life, reuse, recycling and product disposal. (McLaren A., Hardy D. A., and Hughes-Riley T. 2017). The last selected article looks at the topic of smart textiles from a slightly different angle. Through interviews, it explores the level of knowledge for e-textiles production. As a result, none of the participants had all the knowledge to create smart clothing. The paper tried to bridge the gap in knowledge levels by sharing available knowledge, self-learning and learning from existing smart textiles. Despite these efforts, many difficulties arose and, together with this lack of knowledge, led to limited concerns and solutions in terms of getting rid of smart textiles (Perry 2018). Other articles that deal with circular economy and health care issues include (Voudrias 2018) and (van Straten et al. 2021).

It is quite understandable that when dealing with such a complex issue as smart textiles, it is necessary to have multiple experts involved in its production, each with their own area of focus.

Based on the presented research, the basic research questions were formulated. The aim of this paper is to get an answer to these research questions:

- 1) What is the current status of the circular economy, smart textiles in healthcare and their reusability?
- 2) Does the research currently cover all three areas?

3) What is the relationship between these concepts?

3. Methodology

The primary objective of the research conducted in this article is to identify and analyze relevant academic papers within the specified scope of inquiry. This scope encompasses the interconnected domains of smart textiles, healthcare, and circular economy. To systematically explore the relationship among these key terms, comprehensive searches were conducted on two prominent knowledge bases, namely Scopus and Web of Science. Initially, the investigation commenced with a search on Scopus; however, this endeavor yielded no results pertinent to the targeted research area. Subsequently, a parallel exploration on the Web of Science platform also revealed a lack of relevant findings. While some articles were uncovered on ScienceDirect, they only marginally satisfied the predefined criteria for inclusion in the study. In light of the limited direct results from the primary databases, a strategic shift was made to a more nuanced approach. The research team shifted focus towards identifying articles from diverse fields and perspectives that played a pivotal role in establishing connections between smart textiles, healthcare, and circular economy. This deliberate selection process aimed to address the research questions comprehensively.

To refine the search strategy, emphasis was placed on identifying word pair combinations that encapsulate the essence of the research focus. This approach was instrumental in ensuring a nuanced and multidimensional exploration of the intersection between smart textiles, healthcare, and circular economy. The findings derived from this methodological approach form the basis for the subsequent analysis and discussions presented in this article (Table 1).

Table 1. Number of papers in WoS and Scopus databases

Keywords	Nr. of papers	
	<i>Web of Science</i>	<i>Scopus</i>
Smart Textiles and healthcare	375	490
Smart Textiles and Circular Economy	17	13
Healthcare and Circular Economy	71	67

4. Results and Discussion

The first research question is essentially answered by this; these concepts together are not a very well-addressed topic at present. The individual concepts and also the keywords: circular economy, smart textiles and health care, when linked to other areas, have received a lot of attention. However, the interconnection of these keywords is currently a little-discussed topic. It is possible to track down a large number of articles on each topic separately. The answer to research question number two is immediately suggested. Most of the research found touches on the area under study at a few points but does not fully cover all three areas. This can be attributed to the breadth and complexity of the selected areas. The third question is quite extensive, but the articles cited help to establish the relationship between the different areas.

Every year technology moves forward, and science discovers new possibilities, techniques or challenges. For example, the field of production, design and implementation of smart textiles is developing rapidly. This research points to the fact that the issue of their production, reuse and recycling, not only in the healthcare environment, will be one of the major challenges of the coming years. Another reason is the fact that efforts to create a more sustainable environment within the product life cycle are developing. (Veske and Ilén 2021; Wu and Devendorf 2020; McLaren A., Hardy D. A., and Hughes-Riley T. 2017). However, the life cycle of the product itself starts with production. (Veske and Ilén 2021) Here it is a good idea to assess all possible impacts during product design, which may affect the environment, the user and, above all, the life cycle itself. An example of this can be found in the circular economy, where the main idea is to circulate raw materials, components and products because they hardly lose value (What Is the Definition of a Circular Economy?, 2022.).

When manufacturing, it is important to ensure that the following points are met, using quality, durable materials. When manufacturing products, it is important to think that once their lifecycle is over, there are two options. One is to concentrate on the final stage of the product's life cycle when it will be dismantled and the materials used can be recovered as much as possible for recycling or to concentrate on the life cycle itself and try to extend it as much as possible, ideally, to infinity (Veske and Ilén 2021; Wu and Devendorf 2020). The healthcare sector and medical

materials used in aftercare are much more demanding of these requirements than other sectors. It is important to note that estimates predict that the global textile system will grow, and with it, clothing sales. With advances in technology and the availability of smart textiles, smart textiles can be expected to follow a similar upward trend. However, estimates further indicate that the use of clothing will decline. If this is transferred to smart textiles, their use should remain the same. In the case of end-of-life, the phase of repair, dismantling, recycling and reuse of either the product or the materials and components used in smart textiles comes into play (EMF 2017).

4.1 Recycling of Smart Textiles

Most companies are still in the early stages of exploring the circular economy and sustainable development. To mitigate the impacts of smart textile products on the environment, society, and the economy, it is necessary to assess methods of design, manufacturing systems, and, most importantly, recycling processes. Not only companies but also the general public must be involved in the circular economy process to ensure that recyclable waste from consumers ends up where it should. A smart textile product is characterized by the integration of textile material components and technical material components in one product. For the efficient incorporation of textile materials into the circular loop, it is best to use one type of organic textile material for a given product. Organic textile material is biologically completely degradable. During recycling, it is possible to obtain an entirely new yarn, but it is essential that the product does not contain mixtures of other textile fabrics. Organic textile materials include organic cotton, Tencel, hemp, linen, silk, wool, and organic bamboo. If the textile part of the product contains artificial fibers mixed with organic fibers, recycling into new yarn is not possible, and the textile is subsequently downcycled for lower-quality products.

Companies should choose textile materials based on their availability in individual countries. Resources expended on the production and transportation of individual raw materials also need to be accounted for in the circular economy, such as water, pesticides, soil, energy, carbon dioxide, and fossil fuels. The most crucial factor in choosing a textile material is its longevity. An important part of the circular economy is the recycling of products. Damaged products are not necessarily disposed of but can be repaired or parts reused if necessary. For smart textile products, this will include sewing up various small holes, replacing zippers, mending damaged seams, replacing power elements, and soldering damaged wires. It is essential that as technical materials are developed and integrated into the textile structure, the possible repair or replacement of these structures is also addressed.

The most important point of the circular economy is recycling. Recycling will have to be included in the eco-design already so that recycling companies have a clear understanding of where the textile part and the technical part are located. Standards need to be developed to facilitate the market acceptance of new products and increase confidence in the quality of products. This means creating completely new standards for smart textiles and adopting standards already in place from the textile and technical materials sectors. Manufacturers, traders and consumers are increasingly aware of the urgency of standardization in the new field of smart textiles and clothing. The need for standardization of smart textiles and smart clothing is growing as the market grows. The quality of smart textiles and smart clothing on the market needs to be assessed against existing legal requirements contained in EU Directives and national legislation, together with supporting standards. The introduction of new risks, especially about vulnerable consumer groups such as children, disabled and elderly people.

4.2 Standards

An important need for manufacturers and consumers is the development of appropriate test and evaluation methods to ensure the functionality and durability of new products. New standards for smart textiles and smart clothing need to be harmonized with existing EU directives: the General Product Safety Directive 2001/95/EC, the Personal Protective Equipment Directive 89/686/EEC, the Medical Devices Directive 93/42/EC, the Machinery Directive 2006/42/EC, the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment Directive 2002/95/EC, the Waste Electrical and Electronic Equipment Directive 2003/108/EC and the Electromagnetic Compatibility Directive 2004/108/EC. The EU Strategy for Sustainable and Circular Textiles sets out a vision and concrete actions to ensure that, by 2030, textile products placed on the EU market are long-life and recyclable, made as far as possible from recycled fibres, free of hazardous substances and produced with respect for social rights and the environment.

4.3 Process of the Production Cycle

The text describes the content of Figure 1, which is a process diagram depicting the production cycle of a smart product aligned with the principles of the circular economy. The figure outlines the key sub-processes within each significant stage of the overall process, all in accordance with the principles of the circular economy. This visual representation, presented in the form of a flow chart, has been meticulously crafted based on insights derived from the research

documented in the referenced papers. Its primary purpose is to offer a graphical illustration that serves as a blueprint for the future development of smart products, ensuring alignment with the principles and practices of the circular economy. This diagram serves as a valuable tool for understanding and implementing sustainable practices in the design and production of innovative smart products.

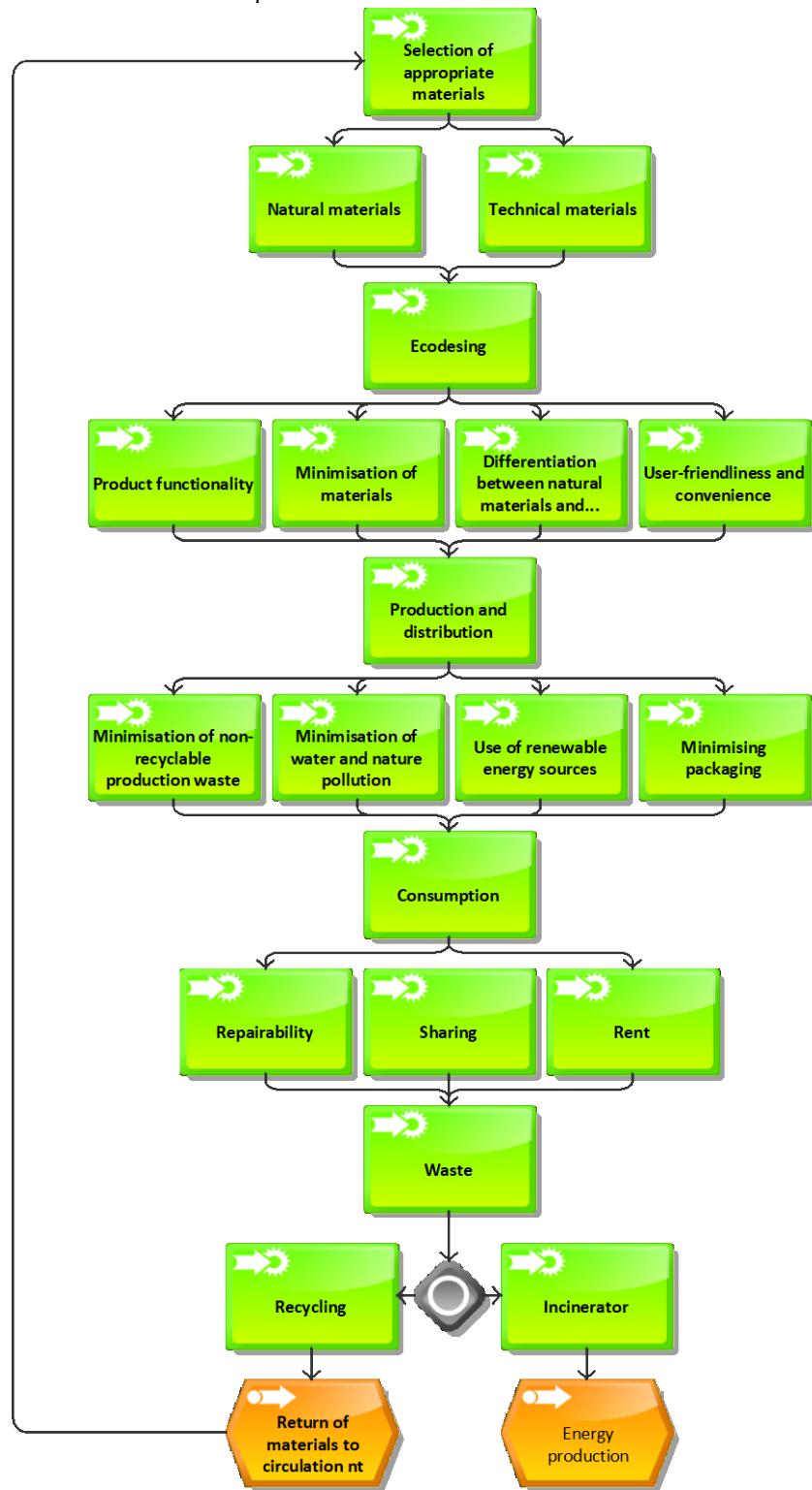


Figure 1. Process of a smart product according to circular economy principles

5. Conclusion

In conclusion, this paper aimed to provide a comprehensive summary of the findings concerning the integration of smart textiles within the context of circular economy principles and their applications in the healthcare sector. The research process undertaken in this study highlighted the interconnectedness of these three concepts and emphasized the importance of addressing this area as a complex and multidimensional topic that requires simultaneous exploration of multiple facets.

The discussion expanded on the significance of considering various aspects when implementing smart textiles, including their practical implications and the limited number of articles exploring the integration of these three concepts. Additionally, the discussion underscored the relevance of the healthcare field, which serves as another crucial link between smart textiles, circular economy principles, and the concept of reuse in healthcare settings. To further advance research in this field, future steps should focus on establishing stronger connections between these domains and identifying areas of common ground.

Furthermore, the article highlighted the importance of considering the life cycle of smart textile products and incorporating long-term impact assessment. This aligns with European policies that advocate for sustainable practices and emphasizes the need to proactively address the future implications of these technologies.

In summary, this study contributes to the existing body of knowledge by shedding light on the integration of smart textiles, circular economy principles, and healthcare applications. It calls for further exploration of the interconnections between these domains and emphasizes the significance of adopting a holistic approach towards the development and implementation of smart textiles within a sustainable and circular framework.

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Biographies

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