ENVIRONMENTAL IMPACTS AND CHALLENGES OF SMART CLOTHING: A REVIEW FROM THE LIFE CYCLE

IMPACTOS E DESAFIOS AMBIENTAIS DE SMART CLOTHING: UMA REVISÃO A PARTIR DO CICLO DE VIDA

IMPACTOS AMBIENTALES Y DESAFÍOS DE LA ROPA INTELIGENTE: UNA REVISIÓN DESDE EL CICLO DE VIDA

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ABSTRACT

Despite the potential of smart clothing, which allows collecting and processing data about the user's conditions and reactions, the environment in which they are inserted and connecting with other artifacts around them, aiming to facilitate daily activities and improve quality of life, problems environmental issues already faced by the clothing sector can be worsened due to the incorporation of electronic components in clothing. Design can contribute to reversing this situation through interventions within the scope of the concept of these products as well as in the associated services and systems. This article presents a review of the state of the art on the topic, with an emphasis on identifying the main environmental impacts and challenges of smart clothing from the perspective of the product life cycle, to contribute to the informational quality of the Designers involved in the project of this product category.

KEYWORDS

Smart clothing; Environmental impacts; Circular Economy.

RESUMO

Apesar da potencialidade de smart clothing, que permite coletar e processar dados sobre condições e reações do usuário, do ambiente em que está inserido e se conectar com outros artefatos a sua volta, visando facilitar as atividades diárias e melhorar a qualidade de vida, os problemas ambientais já enfrentados pelo setor do vestuário podem ser agravados devido a incorporação de componentes eletrônicos nas roupas. O Design pode contribuir para reverter este quadro através de intervenções no âmbito do conceito destes produtos assim como nos serviços e sistemas associados. Este artigo apresenta uma revisão do estado da arte no tema, com ênfase na identificação dos principais impactos ambientais e desafios de smart clothing a partir da perspectiva do ciclo de vida do produto, com o propósito de contribuir para a qualidade informacional dos Designers envolvidos no projeto desta categoria de produtos.

PALAVRAS-CHAVE

Smart clothing; Impactos ambientais; Economia Circular.

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RESUMEN

A pesar del potencial de la ropa inteligente, que permite recopilar y procesar datos sobre las condiciones y reacciones del usuario, el entorno en el que se inserta y conectarse con otros artefactos que lo rodean, con el objetivo de facilitar las actividades diarias y mejorar la calidad de vida, los problemas ambientales ya El problema que enfrenta el sector de la confección puede verse agravado por la incorporación de componentes electrónicos en la confección. El diseño puede contribuir a revertir esta situación a través de intervenciones dentro del alcance del concepto de estos productos así como de los servicios y sistemas asociados. Este artículo presenta una revisión del estado del arte sobre el tema, con énfasis en identificar los principales impactos y desafíos ambientales de la ropa inteligente desde la perspectiva del ciclo de vida del producto, con el propósito de contribuir a la calidad informativa de los Diseñadores. involucrados en el proyecto esta categoría de producto.

PALABRAS CLAVE

Ropa inteligente, Diseño de moda, Residuos electrónicos, Diseño para la sostenibilidad.

1. INTRODUCTION

Computational technological advances in materials and products enable the clothing sector to envision a wide range of possibilities for products with embedded technologies. For instance, clothing that allows the measurement of vital signs and health conditions, geolocation, safety alerts regarding risky situations for the user, among others [1]. Garments that can detect external stimuli and respond to them based on computational data processing are called **smart clothing** [1-2].

The concept of smart clothing is characterized by incorporating electronic components into fabrics and garments to collect and process data about the user's conditions and reactions, the environment in which they are located, and to connect with other artifacts and actors around them, aiming to facilitate the user's daily activities and improve their quality of life [1]. In this category of products, the fabric or the garment itself is the wearable and performs its function with greater naturalness and wearing comfort when compared to other types of wearables, in addition to having contact with a larger area for monitoring and interaction with the body [3].

Despite the potential of smart technologies in the clothing sector, their incorporation generates reflection on the actual environmental, social, and economic impacts [4-5]. From an environmental perspective, the conventional clothing sector already presents various impacts, some quite severe, throughout the product's life cycle, from raw material extraction to product disposal [6]. Thus, the advent of wearable electronic products carries the risk of further increasing these environmental impacts [4-7]. The potential increase in environmental impact in Smart Clothing is mainly due to the profile of the materials used and the energy demanded in data capture and storage. Smart clothing differs from conventional clothing primarily in the materials used in these products; to make clothing smart, it is necessary to incorporate electronic devices and other non-textile materials [1-4]. According to O'Nascimento [8], nowadays, there is a wide variety of materials that can be used in wearable and smart clothing projects, such as materials composed of electroactive and photoactive polymers, elastomers, bio responsive polymers, shape-memory alloys, chromogenic materials, and composite polymers. The incorporation of these materials means that their manufacturing process differs from conventional clothing, and their use also differs from the basic characteristics of non-technological pieces; thus, the environmental impacts also differ and need to be specifically analyzed.

In sustainability, the preventive approach is the most appropriate to address environmental impacts. Additionally, the specific approach of Design for Sustainability allows designers to anticipate the entire life cycle of the product based on the materials and processes involved. In this way, it is also possible to foresee the product's environmental impacts and make decisions that mitigate these impacts [9].

In the case of smart clothing, it is important to investigate environmental impacts and challenges based on this approach, as these products are still in the development phase and gaining market space. Therefore, an anticipatory study is relevant. This article is an excerpt from larger research on the environmental sustainability of the end of life of smart clothing. To broadly understand this type of product, this article aims to explore the existing literature to identify the main environmental impacts and challenges of smart clothing from a holistic view of the product's life cycle.

1.1 Defining Smart Clothing

The concept of smart clothing has a history that can be traced to the 1960s. At that time several advances occurred in the computational area, allowing the development of new technologies and new products with electronic data processing and communication systems. That period witnesses the creation of the concept of wearable technologies, which can be defined as an innovation approach that uses the body as the basis for the arrangement of electronic technologies, enabling the incorporation of sensors and actuators in proximity of it and the transformation of the functioning of artifacts to a new level, the electronic computational level [8]

One of the similarities between smart clothing and wearables is the relationship with the body. Wearables are computational technologies or electronic sensory devices that are worn on or near the body (Barfield and Caudell, 2001; Tehrani and Michael, 2014; Bower and Sturman, 2015). Another similarity is the digital and computational aspect of the wearable, independent of its function and relationship with the user's body (see Figure 1).

Figure 1: Example of smart clothing available on the market.

Source: Ottobock website (2024).

The Ottobock piece is a neuromodulation suit for relaxing spastic and tense muscles, activating weak muscles and relieving related pain, made for people with neurological diseases that affects the body in a degenerative way [41].

Hexoskin shirt (see Figure 2) offers biometric smart shirts equipped with sensors that monitor heart rate, breathing rate, and activity levels.

The data collected by the shirt is transmitted to a smartphone app or a compatible fitness device for analysis and tracking [42].

2. METHODOLOGICAL PROCEDURE

This article adopts a qualitative approach with an exploratory-descriptive character and a basic nature. To identify relevant themes, gather preliminary information for formulating the research problem, and generate keywords for the next stage of the Systematic Literature Review (SLR), an initial Non-Systematic Literature Review (NSLR) was conducted. Subsequently, the SLR was carried out to collect data and critically analyze the existing literature on the topic, focusing on identifying key emphases and concepts involved.

During the NSLR, searches were conducted in the Brazilian Digital Library of Theses and Dissertations, CAPES Journals, and Google Scholar databases for publications made from 2013 to 2023. The focus was on analyzing the literature on smart clothing, environmental impacts, and related areas pertinent to this study. This stage aimed to gain a better understanding of the constructs involved, the relationships between them, and the identification of key terms and authors.

The protocol used to conduct the SLR was proposed by Conforto, Amaral, and Silva [10]. This stage focused on understanding information related to smart clothing and the environmental impacts of the product's life cycle. The search protocol was developed based on the question, "What are the environmental impacts of the life cycle of smart clothing?" The search period covered 2018 to 2023, and searches were conducted on the Google Scholar and CAPES Journals platforms. The keywords used to generate the search strings were electronic devices, electronic components, sustainability, clothing, fashion, garment, end-of-life, waste, wearables, and smart clothing. The research scope was limited to peer-reviewed international journals published in English, with the first 30 results in order of relevance from the application of the search strings being considered for Filter 01 (title/abstract). Exclusion criteria included the presence of terms such as material engineering, operational processes, digital fashion, business models, and other terms unrelated to design.

Table 1 shows the Systematic Literature Review protocol.

Figure 1: Hexoskin.

Source: Hexoskin website (2024).

Search period	6 years (2018-2023)
Journal Profile	Peer reviewed
Language	English
Search Criteria	Top 50 in order of relevance
Inclusion criteria	Smart clothing, sustainability, end of life, e-waste, IoT, design, fashion, life cycle
Exclusion criteria	Fiber and material engineering, operational process, digital fashion, business models
Search Platform	CAPES periodicals, Google Scholar, Web of Science
Filters adopted	Filter 1: title, abstract and keyword analysis; Filter 2: reading introduction, method, discussion, and final considerations; Filter 3: complete reading
Search fields	All of them
Search strings	"smart clothing" AND "sustainability" "smart clothing" AND "electronic waste" "interactive clothing" AND "electronic waste" AND "sustainability" "smart clothing" AND "life cycle" "e-textiles" AND "end of life cycle" "intelligent clothing" AND "circular design" "wearables" AND "iot in fashion" "e-textiles" AND "electronic waste" AND "end of life cycle" "smart garments" AND "sustainability" AND "end of life cycle" "iot in fashion" AND "sustainability"

Table 1: SLR protocol.
Source: Author (2024).

Only the articles that met the criteria presented were included, which were important for clarifying ideas and constructing the literature.

3. RESULTS

To analyze the results from the consulted literature based on the product's life cycle, they were divided according to the stages of **pre-production, production, distribution, use, disposal,** and **design.**

3.1 Clothing Life-Cycle

The clothing sector already is a complex, wide and heterogeneous arrangement of a large diversity of stakeholders, with an also large variety of relationship dynamics and inputs/outputs [43].

Based on Modefica [44], Gwilt [45] and Salcedo [46], the clothing life cycle can be described as having eight phases:

1) pre-production: the pre- production is the phase where the materials are extracted, from plantation and harvest in the case of natural and artificial fibers, or from petroleum, in the case of synthetic fibers;

2) production: The production phase characterizes the spinning, weaving and dyeing of fibers, making them ready to be commercialized and transported to clothing producers as fabrics;

3) transportation;

4) design: the design phase covers the activities of concept definition, selection of fabrics and trimmings, mapping the collection's product mix and development modeling process, this being the step that will shape the subsequent impacts of launched products [45];

5) confection: the confection and production phase are when the fabric turns into clothing, using techniques such as modeling, cutting and sewing, including prototyping and transport for factions. In turn, distribution is the stage where products go to the places it will be sold to the final consumers;

6) distribution;

7) use and maintenance: after transported and sold, the use stage is, according to Gwilt [45], the way in which clothing is used and maintained and carried out, it directly implies the conditions and period of time that will take to be discarded;

8) disposal: finally, the last phase of a clothing product is the disposal, in it, textile articles are discarded, becoming post-consumer textile waste. Disposal activity can be carried out in different ways, it is directly linked to the behavioral aspect of the consumer. Nonetheless, the disposal phase does not mean that the textile can not be used anymore.

3.2 Pre-production

The production of electronic components and fabrics requires large amounts of energy and resources for the manufacturing of Smart Clothing. Currently, no country can produce all the materials used in ICT - Information and Communication Technology - products, as a substantial number of mineral deposits are only found in specific locations [11].

The manufacturing of these electronic devices requires a diverse mix of ferrous and non-ferrous metals, ceramics, polymers, printed circuit boards, and more than 1,000 other substances [12-13]. In addition to the extraction of these materials, there is also the refining of these minerals, metals, and polymers, which involves processes such as laser cutting, electrical welding, and electroplating, all of which generate pollutants in the air, water, and soil [14].

The production of fabrics and garments also represents a significant environmental challenge, especially considering that the fashion industry is one of the most polluting in the world. According to Gurova et al. [11], this industry is responsible for a considerable portion of global wastewater, accounting for about 20% of the total, and contributes approximately 10% of global carbon emissions. For example, an average kilogram of textile has a carbon footprint of 15 kg.

Also, to select materials for smart clothing it is necessary to comprehend the combination of the textiles with the electronic devices and other components. As well, the designer needs to be careful with the compatibility of the life-cycle spans of the textile materials and the electronics [11]. This could create barriers for the use of natural fibers, for example, since the life span of cotton for example is much lower than electronics components.

Nevertheless, all the fibers have virtues and problems in terms of sustainability. In the smart clothing context, it is important to analyze how to balance the impacts from the products' life cycle [11], for example by comprehending the impacts of the extraction, the combination methods of the textiles with the electronics, the usability and comfort, the washability and ease of care, the total life span and the post-use options (like reuse, repair and recycle).

3.3 Production

The sustainability of a smart wearable, as emphasized by Dulal et al. [7], depends on the individual sustainability of each component and its respective production processes. The production aspects of smart clothing throughout its life cycle, from raw material extraction to disposal, can have negative environmental impacts, such as the use of non-renewable and scarce resources, water contamination, energy consumption, and greenhouse gas emissions [4]. The level of integration between electronic devices and textiles also significantly influences the impact on clothing production, not only by enabling recycling and reuse but also by facilitating cleaning, washing, and technological upgrades.

The usual clothing production process, as detailed by Li et al. [14], involves steps such as spinning, dyeing, cutting, sewing, and finishing. Chemicals are often used to improve aesthetics and usability, resulting in severe pollution. Moreover, significant carbon dioxide emissions, high water demand, and the use of hazardous chemicals occur both during cutting and sewing and in the finishing stages [11].

The production of Information and Communication Technology (ICT) components, as observed by Gurova et al. [11], requires large quantities of toxic materials, such as semiconductors, printed circuit boards, and precious metals like gold, silver, palladium, platinum, base metals, and heavy metals like lead, mercury, arsenic, chromium, among others [15]. However, this combination of electronic materials with textiles can result in the generation of fiber dust, tons of metal scrap, and fabric remnants [14].

If well designed, the toxic materials do not present any risk for the user as they stay in closed containers. The risks they present are related to the pre-production, production and disposal phases, when they normally are not isolated.

3.4 Distribution

The distribution of smart clothing involves transporting the products from factories to retail locations and, ultimately, to consumers. However, this process has a significant environmental impact, as highlighted by Gurova et al. [11]. Carbon emissions and air pollution are direct consequences, especially when fossil fuel-dependent modes of transportation, such as trucks and airplanes, are used. Simplifying supply chains by utilizing local production facilities is one of the suggestions proposed by Gurova et al. [11] to reduce this environmental impact, as the complexity and geographical dispersion of supply chains, especially for the production of textiles and electronic equipment, make these distribution challenges an increasing environmental concern.

Additionally, the incorporation of electronic materials and components makes the global manufacturing process quite different from conventional clothing, involving the use of global supply chains and, therefore, a higher demand for transportation.

The transportation and distribution of smart clothing is related to energy consumption, greenhouse gases emissions, and air pollution, which contributes to this industry's environmental impacts. Despite the contribution of the dematerialization on the ICT industry, for example with digital and online software instead of a CD-ROM or physical products, in the smart clothing sector it is still necessary to transport some devices to produce the product and to make it available to the consumer.

3.5 Use

When using smart clothing, the environmental impact increases due to the significant energy consumption required to keep them operating. The electronic components integrated into smart textiles consume more energy compared to common electronic devices and regular clothing. This increase in consumption stems from the additional communication and control unit inherent in smart IoT devices, which demands an energy surplus [16]. As a result, even when tasks are completed or the garment is turned off, the smart clothing continues to consume energy, keeping the system active remotely. This higher energy demand puts additional pressure on the electrical grid, which largely depends on energy supplied by hydroelectric plants, in the Brazilian context. These plants emit greenhouse gases, contributing to environmental pollution and global temperature increases, thereby exacerbating sea level rise [16].

Another factor at this stage is the early disposal of wearables due to users' lack of familiarity. According to Ju et al. [17], users often face difficulties during their initial uses, which can lead to frustration and the perception that the product does not meet their expectations or is unnecessary, resulting in the discontinuation of its use. Additionally, the lack of proper collection points for appropriately disposing of smart clothing when it stops functioning is also a significant challenge [18]. These two factors combined contribute to a growing environmental impact.

The functional aspects of smart textiles and clothing are a critical component of use. However, these functions do not necessarily translate into a longer-lasting user-product attachment, and individuals may still abandon the use of these technologies due to factors that also relate to the behavioral level of design, such as the difficulty of maintenance and care for the products and the lack of direct application of the collected data in daily life [19].

Especially for lay users, maintaining smart clothing can negatively affect ease of use and become one of the primary reasons for unsustainable user behavior. In addition to the inherent care and maintenance activities of traditional textiles and clothing, such as laundry, ironing, and repairs (e.g., stitching, buttons, holes, etc.), new activities and skills are required for the maintenance and care of smart textiles and clothing. Charging, accessing and/or storing collected data, specialized laundry requirements (e.g., removing hardware components, hand washing) are examples of new and additional maintenance and care activities [19].

3.6 Disposal

One of the main stages of the life cycle that involves concerns regarding environmental impacts is disposal. In addition to the difficulties already faced in the garment sector with post-use waste disposal, smart clothing presents a new environmental challenge: electronic waste (e-waste) generated from the garments themselves [4]. E-waste is considered a non-homogeneous and complex mixture of potentially toxic components [20-21].

The substances released by e-waste can be classified as hazardous or non-hazardous, with hazardous substances including those with characteristics such as flammability, corrosivity, reactivity, toxicity, pathogenicity, carcinogenicity, teratogenicity, and mutagenicity. These include heavy metals, polycyclic aromatic hydrocarbons, polybrominated diphenyl ethers, and polychlorinated dibenzo-p-dioxins; non-hazardous substances include metals such as Cu, Se, Pt, and Ag, among others [22-25].

The main materials used in smart clothing are sensors, conductive wires and fabrics, microcontrollers, LEDs and display screens, batteries, actuators, connectors and cables, antennas, wireless connection modules, and insulating materials [8]. Despite the miniaturization of these devices to maintain comfort, flexibility, and wearability requirements, the components used contain potentially toxic and scarce materials when improperly disposed [26], including high-risk environmental materials such as lead, mercury, cadmium, chromium, halogenated or brominated flame retardants, chlorinated substances, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons, and refrigerant gases [27-33]. Improper disposal of these materials can negatively impact the environment and various forms of life, including human health.

In the context of disposal, the recycling process itself can contribute to the release of hazardous primary electronic waste residues (Hg, Pb, Cd, PCBs, and other secondary toxic e-waste substances, including polycyclic aromatic hydrocarbons, dioxins, and furans), primarily resulting in soil and water contamination, soil solubilization, leaching, and bioaccumulation [34-35].

To analyze disposal, it is also important to understand the forms of technology integration into clothing, as this impacts the environmental challenges of the product and how it will be dismantled and discarded. There are two approaches to making smart clothing from the textile perspective: first, producing electronic textiles (e-textiles) and then making the garments; or first making the garments and then incorporating the technology into them. The first approach often results in products that are more difficult to dismantle, as electronic components may be directly incorporated into the fibers and textile structure [4]. Another possible approach, considering the electronic nature, is to create circuits and devices using various materials, which are then integrated into the garments and textiles, a principle related to the maker movement. Alternatively, ready-made solutions from manufacturers can be used and integrated into pre-made garments.

3.7 Design

The development of products through design for sustainability involves various aspects, including the stages of pre-production, production, use, and end-of-life, and the application of strategies for prevention, minimization of occurrences, and mitigation of environmental impacts already at the conceptual development phase [36]. In the context of environmental sustainability, one of the potential contributions of design lies in the ability to design the artifact considering the entire life cycle before it is produced, meaning there is a possibility to foresee the product's impact before it exists [37].

By anticipating the product's impacts in every aspect that requires decision-making, such as material selection, processes, and final performance, it is possible to apply strategies at the conceptual phase that address each impact and make the product more suitable with better environmental performance indicators [37]. Factors such as washability, durability, aesthetics, ease of use, programming, maintenance, and updates must be considered to avoid premature disposal of such products.

3.8 Challenges on reuse, repair and recycle of Smart Clothing

Unlike traditional clothing, smart garment pieces contain integrated electronic components, like sensors, batteries, and microcontrollers [1, 38]. In the context of end-of-life approaches, the technological complexity makes the reuse process different from when it comes to conventional clothing. Strategies aiming at reuse within the scope of the artifact and the combination with systems to support transferring the product can increase the ease of extending the life cycle and favor the implementation of reuse [9, 36]. Examples include second-hand stores, and banks of EEE parts for reuse and exchange schemes.

The reparability of smart garments also becomes a problem since both materials have distinct repair needs. Clothes are normally repaired for small issues like holes, seams, or hems unraveling, while basic electronics repairs often involve replacing easily accessible batteries and other components [39]. When it comes to smart clothing, these repair methods, which are seen as straightforward, become difficult following the level of integration between the electronics and fabric. Insufficient reparability promotes short product life cycles through premature obsolescence [39, 40]. In the analysis of specific strategies to enable repair, it was demonstrated that its application demands adaptation in how clothing companies usually operate, relating to customers and in the conventional market paradigm, which aims to sell new products. In the case of making repairs possible, the manufacturer and/or retailer must pay attention to after-sales, especially in cases where parts for exchanging and adapting the product are not available at the time of purchase. The possibility of providing services that contribute to extending the life cycle was also identified, such as software upgrades and updates and specific spaces for repair and customization within stores.

In the recycling matter, currently, there are some regulations for the disposal of components that contain WEEE (Waste Electrical and Electronic Equipment) that could be applied to the disposal of smart clothing

[39]. Still, these regulations have gaps regarding smart clothing specifications and particular issues [39]. Even though smart clothing is already reaching recycling facilities, they are often discarded incorrectly because of the lack of proper infrastructure to handle the material [4]. Additionally, the recycling issues are associated with the challenge of achieving the economic and financial viability of managing the electronic waste present in Smart Clothing, since smart clothing pieces have a low mass of electronic components per product of electronic components when compared to other types of EEE (EPPINGER et al. 2022).

3.9 Life-cycle impacts

The environmental implications of the presence of electronic components on clothing is better explained when structured around the life cycle stages, as illustrated in Figure 3. To facilitate the comprehension of the content, the table 2 shows the whole life cycle of smart clothing and the impacts regarding each phase.

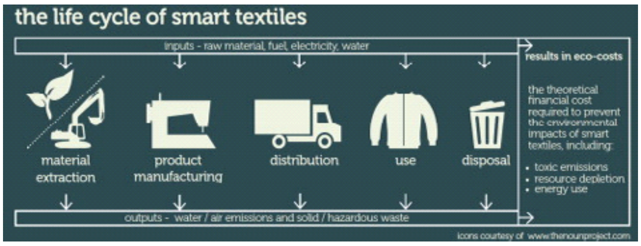

Figure 3: Smart clothing environmental impacts.

Source: Velden, Kuusk and Kohler (2015).

Life-cycle phase	Impacts
Pre-production	• Requires large amounts of energy and resources, such as mix of ferrous metals, non-ferrous metals, ceramics, polymers, printed circuit boards and more than 1000 other substances; • Refinement of these ores end up generating pollutants in the air, water and soil; • Fabric pre-production is responsible for a considerable portion of global waste water, representing around 20% of the total, in addition to contributing approximately 10% of global carbon emissions;
Production	• Chemicals pollution; • Cutting and sewing and in the finishing stages, there are significant emissions of carbon dioxide, a large demand for the use of water and dangerous chemicals; • Use of toxic materials; • Combination of electronic materials with textiles can result in the generation of fiber dust, tons of metal scrap and fabric scraps;
Distribution	• Carbon emissions and air pollution are direct consequences, especially when using modes of transport dependent on fossil fuels, such as trucks and planes;
Use	• Electronic components integrated into smart textiles consume more energy compared to ordinary electronic devices and clothing This increase in consumption arises from the additional communication and control unit inherent in smart IoT devices, requiring a surplus of energy (Yugank et al., 2022). • Energy production emits greenhouse gases, contributing to environmental pollution and rising global temperatures, thus exacerbating sea level rise (Yugank et al., 2022).
Disposal	• Generates a new environmental challenge: electrical and electronic waste (WEEE) from clothing items; • Substances released by WEEE can be classified as dangerous, including heavy metals, polycyclic aromatic hydrocarbons, poly dibenzofurans, ethers brominated diphenyls and polychlorinated dibenzo-p-dioxins;

Table 2: Smart clothing environmental impacts.

Source: Velden, Kuusk and Kohler (2015).

This table summarizes the environmental impacts of smart clothing and can be used to compare conventional clothing, waste of electronic equipment and clothing with technology embedded. These three types of product are related and can be explored together to comprehend smart clothing challenges, impacts and possible solutions.

4. DISCUSSION

When analyzing the environmental impacts of smart clothing and comparing it with the conventional clothing sector, it is possible to verify that this type of product increases existing environmental challenges, since impacts occur at all stages of the life cycle of both the clothing and of electronic devices together. Therefore, additional negative environmental impacts can be identified throughout the product life cycle. From the extraction of materials in pre-production, to production processes, smart clothing demands the application of materials and manufacturing procedures different from conventional textiles, such as toxic materials, semiconductors, printed circuit boards in precious metals such as gold, silver, palladium, platinum, base metals and heavy metals such as lead, mercury, arsenic, chromium, among others (Huang et al., 2022), meaning that the environmental impacts of these clothes are not restricted to those linked to textiles and apparel, but come close to the impacts of electrical and electronic equipment.

The use and maintenance of these products also differ from the washing, drying and ironing of conventional fashion products, as the electrical and electronic equipment present in the clothes require greater energy and water consumption for their electrical operation, in addition to requiring specific cleaning care to avoid damaging the product equipment. Disposal also presents itself as a problematic step within the environmental scope, since the current infrastructure for repairing and recycling clothing and electronic equipment does not support products that integrate clothing and electrical and electronic technologies.

Smart clothing adds further complexity to the Design process as it has the layer of digital processing and the associated ethical considerations. Complexity is enhanced with issues such as data security, ethical and legal issues of data ownership, user privacy, interoperability (connectivity between artifacts from different manufacturing companies), higher complexity in interface use, social acceptance, increased user dependence on technologies, decreased of human contact and excessive use of unnecessary fashionable technologies for commercial purposes only. In this context, the fashion designer needs to be attentive and capable of addressing all these issues raised during the development of smart clothing, so that the positive impacts outweigh the setbacks.

Under the waste hierarchy “prevention” is the most effective strategy to deal with environmental impacts. In this respect Design for Sustainability approaches at the conceptual stage can anticipate solutions for the entire life cycle of smart clothing. Such approaches can contribute to predict/envision the environmental impacts of the product and make decisions that mitigate these impacts (Manzini and Vezzoli, 2008). In the case of smart clothing, it is important to investigate the environmental impacts and challenges based on this approach since these are products that are still in the development phase and gaining space in the market, so an anticipatory study is pertinent.

In addition to the aforementioned advantages, smart clothing presents potential benefits for the challenges presented by sustainability. There are, also, a growing number of solutions that substantially mitigate the inherent environmental impacts of smart clothing. Tat et al. (2022) presents solutions that are capable of capturing movement or heat from the user and transforming it into energy to power various devices or the smart clothing item itself. The insertion of electronic devices close to the body allows another energy source to be associated with the biomechanical energy supply, as only one source may be insufficient to generate electricity or fail due to energy supply circumstances that are sometimes unlikely to be available, such as solar irradiance in rainy or cloudy weather. As smart textiles are diverse and can link multiple parts of the body, they could also bring together multiple energy sources, producing a hybrid system. For example, a structured micro textile cable, using the shuttle-flying process on an industrial loom to weave polytetrafluoroethylene with photoanode and copper electrode strands, could simultaneously harvest solar and biomechanical energy (i.e., when exercising in the sun) (Tat et al., 2022).

Still in terms of environmental benefits, smart clothing allows the development of products that consume less energy than other electronic devices for the same function. Also compared to other non-wearable electronic devices, smart clothing has the advantage of requiring the miniaturization of components and consequent minimization of the use of resources, as they are pieces that need to be comfortable, flexible and aesthetically pleasing (Tat et al., 2022).

5. FINAL CONSIDERATIONS

Finally, it was possible to analyze the impacts of smart clothing from the product life cycle concept, highlighting the potential of design as a development approach with environmental awareness, particularly regarding products based on emerging technologies, such as smart clothing. Additionally, anticipatory studies of the environmental impacts and challenges of this type of product can contribute to risk mitigation and the development of intrinsically more sustainable products, given that they are not yet widely available in the market and are at an early stage of innovation.

This study contributes to the expansion of research in Brazil on smart clothing and to the understanding of environmental impacts as a means to guide the development of heuristics and guidelines for these products based on Design for Sustainability. The study also advances environmental awareness in the design field, which, beyond theory, should address theoretical and practical aspects related to the product life cycle to develop sustainable solutions, especially for products still in the exploration phase and with embedded computational technologies.

For future research, it is recommended to explore topics such as the social and economic impacts of the smart clothing life cycle, as well as seeking solutions for the challenges identified in the literature.

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