Smart Clothing and End-of- Life: Bibliographic Review on Hardwares, Structures and Production Technologies

Roupas inteligentes e final de ciclo de vida: Revisão bibliográfica sobre dispositivos, estruturas e tecnologias de produção

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Abstract

Smart clothing differs from conventional garments due to the integration of electronic components, which directly influences their structure, durability, and end-of-life management. This paper analyzes the state of the art in hardware, textile structures, and production technologies related to smart clothing, focusing on sustainability and circularity. A systematic literature review identified key strategies for integrating electronic components into textiles while ensuring disassembly and recyclability. The results indicate that different approaches, such as perceived technology and seamless technology, present distinct challenges and opportunities. Seamless technology, where electronics are embedded directly into the textile structure, requires greater attention to disassembly to ensure components can be separated without compromising materials. On the other hand, perceived technology, which often relies on modular or externally attached solutions, may simplify this process but still demands design strategies that ensure maintenance and durability. The study emphasizes the importance of strategically selecting materials and integration methods, reinforcing the need for Design for Disassembly and Design for End-of-Life approaches for sustainable smart clothing development.

Keywords: Smart Clothing; End-of-Life; Product structure

Resumo

Roupas inteligentes diferem das convencionais devido à integração de componentes eletrônicos, o que influencia diretamente sua estrutura, durabilidade e gestão do final de ciclo de vida. Este artigo analisa o estado da arte em hardwares, estruturas têxteis e tecnologias de produção associadas a roupas inteligentes, com foco na sustentabilidade e circularidade. A revisão sistemática da literatura identificou estratégias-chave para a integração de componentes eletrônicos aos têxteis, considerando desmontagem e reciclabilidade. Os resultados indicam que diferentes abordagens, como tecnologia percebida e tecnologia incorporada, apresentam desafios e oportunidades distintas. A tecnologia incorporada, onde a eletrônica é incorporada diretamente à estrutura têxtil, requer maior atenção à desmontagem para garantir que componentes possam ser separados sem comprometer os materiais. Já a tecnologia percebida, que geralmente utiliza módulos removíveis, pode simplificar esse processo, mas ainda demanda estratégias projetuais que garantam manutenção e durabilidade. O estudo enfatiza a importância de selecionar materiais e métodos de integração de forma estratégica, reforçando a *necessidade de abordagens como Design para Desmontagem e Design para Final de Ciclo de vida para o desenvolvimento sustentável de roupas inteligentes.*

Palavras-chaves: *Roupas inteligentes; Final do ciclo de vida; Estrutura do produto*

1. Introduction

Smart clothing differs from conventional clothing especially because of the materials used in these products. In order to manufacture a Smart Clothing it is necessary to incorporate electronic devices and other non textile materials (Jiang et al., 2021; Kohler, 2013). According to O´Nascimento (2020), there is a wide range of materials nowadays that can be used in wearables and smart clothing projects, such as materials composed of electroactive and photoactive polymers, elastomers, bioresponsive polymers, memory shape alloy, chromogenic materials and composite polymers. The designer should know how to select materials based on project scope, characteristics of materials, price, availability and sustainability factors. O´Nascimento (2020) argues that the advances in smart clothing until nowadays are majorly in the electronics area, resulting in products with problems of wearability, comfort and aesthetical issues. This brings to designers a new challenge to create pieces with useful technology but also a good adequacy to the body movements and limitations, besides the environmental aspects.

One of the critical aspects of smart clothing development is the environmental impact of embedded electronic components. As Veske and Ilén (2021) argue, understanding the ecological implications of these materials is essential for mitigating potential negative effects, particularly in scenarios where early disposal is likely. A comprehensive understanding of the hardware, structural composition, and textile integration of smart clothing can support more sustainable design choices. Strategies such as improving product upgradability, facilitating the disassembly of electronic components, and optimizing material selection can contribute to reducing environmental impacts at the product's end-of-life stage.

In this sense, this paper aims to explore the state-of-the-art in hardware, textile structures, and production technologies associated with smart clothing. By examining these aspects, this study seeks to provide insights into how designers can integrate technology into garments while considering sustainability and product end-of-life, using concepts such as Design for EoL and Design for Assembly and Disassembly.

2. Methodological Procedures

This paper has exploratory objectives, a descriptive nature, and a qualitative approach, as it aims to analyze the state of the art in smart clothing, including its hardware, structures, and production technologies. This research contributes to the generation of knowledge on garments incorporating emerging digital technologies and end-of-life studies, given that the structure and materials of a product are directly related to its assembly and disassembly—essential criteria for end-of-life management (Sampaio et al., 2018).

To identify relevant themes, gather preliminary information for defining the research problem, and select keywords for the next stage of the Systematic Literature Review (SLR), an initial Non-Systematic Literature Review (NSLR) was conducted. Subsequently, to collect data and critically analyze the existing literature on the topic—focusing on identifying key concepts and areas of emphasis—the SLR was carried out. The NSLR involved searches in the CAPES Journals database and Google Scholar, covering publications from 2018 to 2024. The focus was on analyzing the literature on smart clothing, product structure, and its relationship with end-of-life management, as well as relevant related fields. This stage aimed to gain a deeper understanding of the constructs involved, their interrelations, and the identification of key terms and authors.

The protocol used to conduct the SLR was proposed by Conforto, Amaral, and Silva [10]. The search protocol was developed based on the question: "What materials, structures, and production technologies are used in smart clothing?". The keywords used to generate search strings were electronic devices, electronic components, sustainability, clothing, fashion, garment, end-of-life, waste, wearables, and smart clothing. The research scope included international, peer-reviewed journals published in English. For inclusion in Filter 01 (title/abstract), the top 30 most relevant results based on the applied search strings were considered. Exclusion criteria included the presence of the terms material engineering, operational processes, digital fashion, business models, and other terms unrelated to design.

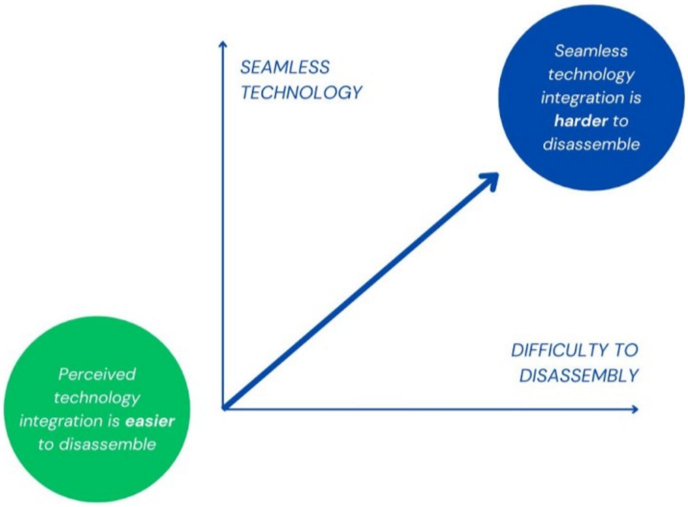
3. Results on smart clothing hardwares, structures and production technologies

Projects in the field of smart clothing require the designer to decide from electronics materials, textiles materials, fabrication process as well as the digital interaction forms. The late ones include issues such as inputs (what is the trigger to activate the product function) and outputs (what is the product response after the trigger and processing) from the technology. Designer´s decision-making should consider all of these aspects in an integrated way, according to the user needs associated with the specific smart clothing that is being developed (O´Nascimento, 2020).

In electronics, the structural and physical part of a device is called hardware, and the operational system that executes the activities is called software. This implies a whole new epistemology associated with clothing since normally software is not associated with this type of product. Hardware and software are both relevant when considering smart clothing end of life stages but from an environmental perspective a higher priority is directed towards the electro-electronic hardware since it is these physical parts that effectively constitutes e-waste when dealing with smart clothing.

There are different strategies to conceive smart clothing. Depending on its expected functions, the project can start from the fabric: making the electronic textile (e-textile or e-fabric) first and then producing the clothes. Another approach could focus on designing the service around a expanded value offer (ex: monitoring falls of elderly within the household) and then designing the appropriate cloth that fit that service, resulting in a product with seamless technology integration. Alternatively, a given project can start on the clothing design itself and afterwards focusing on the integration of the electro-electronic technology and related services, resulting in a product with perceived technology integration. The first approach, the seamless technology, usually results in products harder to disassemble, once the electronic components can be directly incorporated onto the fibers and the textile structure (Kohler, 2013). The latest approach, the perceived technology, can adopt on-the-shelf proprietary solutions or open-source solutions and either standardized or customized. Very importantly, the product development strategy will affect the environmental performance regarding the end of life stages (see Figure 1).

Figure 1: Smart clothing fabrication method and disassembling ease.



Source: Author (2024).

O´Nascimento (2020) and the open source wearables projects platform Kobakant (2017) presents the most common materials used in smart clothing projects. They propose to divide them in categories based on their characteristic and main function, as illustrated on Table 1.

Table 1: Typical materials employed on smart clothing

Category	Function	Exemple
Conductive fabrics, threads and yarns	Enable the flow of electricity and often used for creating soft, flexible circuits in smart textiles	• Copper conductive fabric • SaniSilver fabric • Elitex • Bekinox
Sensors	Integrated into smart clothing to gather data	• Accelerometers for motion sensing • Gyroscopes for orientation sensing • Flex sensors to detect bending • Heart rate monitors • Temperature sensors

Microcontrollers	Control and process data (for example Arduino or Arduino Lilipad for wearables and Raspberry Pi for more complex projects	• Arduino or Arduino Lilypad (for wearables) • Raspberry Pi
LEDs and Display Components	Can be used for visual feedback or information display in the clothing	• LED strips • OLED (Organic Light-Emitting Diode) displays
Batteries	Power sources, such as lightweight and rechargeable batteries	• Li-Po (Lithium Polymer) batteries
Actuators	Interfere directly with the environment, that is, a data output from the microcontroller to activate some controlled device or object	• Wearable actuators • Buzzers
Connectors and Cables	Link different components of the circuit	• Flexible and lightweight cables
Antennas	If the project involves wireless communication, antennas for Bluetooth or other connectivity options	• Wearable antennas
Wireless communication modules	Connectivity with other devices	• Bluetooth modules (Bluetooth Low Energy - BLE) • Wi-Fi modules
Controllers and Switches	Integrate buttons, switches, or capacitive touch sensors for user interaction; Use conductive fabrics or threads to create touch-sensitive areas	• Buttons • Fabrics • Threads
Enclosures and insulating materials	Protect electronic components from environmental factors like moisture or physical damage and to prevent short circuits	• Insulating materials

Source: Author (2024) based on Kobakant (2017) and O´Nascimento (2020).

The definition of the structure of the product of smart clothing needs to consider the hardness characteristics of the materials and the part of the body that will wear the piece. Hardness is an attribute that can be found in electronics textiles and clothing, being described from soft materials to hard materials. For Bochetta et al. (2020), soft materials are often found on portable flexible energy storage, conversion and biosensor devices. All of them can be worn on soft and curved surfaces. In turn, hard materials are the devices that cannot be shaped as soft and curved surfaces.

After knowing the materials, it is important to understand the manufacturing methods to incorporate the electro-electronic devices to both fabrics or to an existing clothing. The electronic-textile-clothing nexus influences end-of-life options, once it is related to the product maintenance, washability and disassembly. Tseghai et al. (2020) adds flexibility, low weight, and robustness to these features. These features depend on the properties of the electro-electronic components as well as the fibrous materials, which may be influenced by the post-treatment and integration techniques. O´Nascimento (2020) presents that technology integration can be implemented by using manual or digital techniques, like sewing or 3D printing, respectively. Despite starting the Design project of Smart Clothing with the intended function, it is important to comprehend the materials and integration forms to select them according to the project scope. Table 2 shows the most common combination of electro-electronic technologies to fabric and clothing.

Table 2: Most common combination of electro-electronic technologies to fabric and clothing

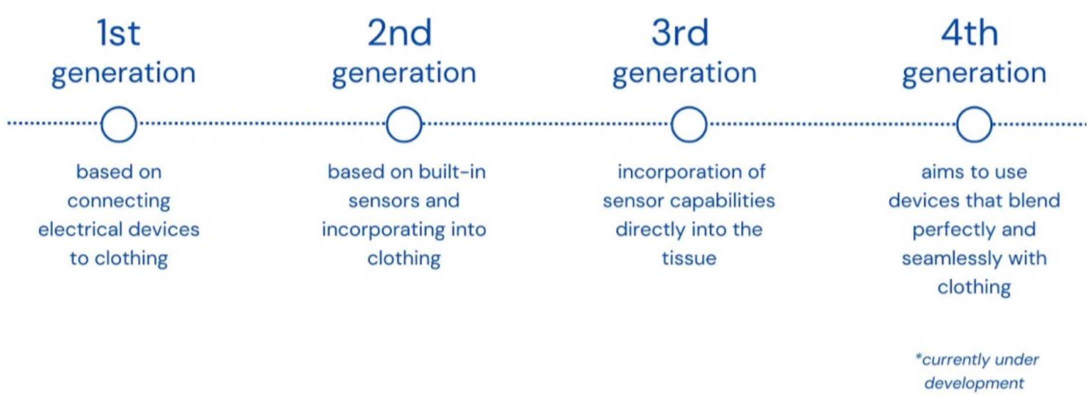
Combination method	**Description**
Sewing and Embroidery	Conductive Thread: Sewing circuits using conductive threads to connect electronic components; Embroidery Techniques: Embedding conductive threads in patterns or directly attaching electronic components with specialized stitches;
Iron-On or Heat Transfer	Applying heat-activated adhesive patches containing electronic components onto fabric;
Printed Electronics	Screen Printing: Using conductive inks to print electronic circuits directly onto fabric; Inkjet Printing: Precision printing of conductive materials onto textiles;
Flexible Printed Circuit Boards (FPCBs)	Soldering Components onto FPCBs: Attaching electronic components to flexible circuits; Embedding FPCBs into Fabric: Integrating flexible circuit boards directly into the fabric structure;
Knitting and Weaving	Conductive Yarns: Using yarns with conductive properties in knitting or weaving projects; Integrating Components into Fabric: Embedding electronic components directly into the textile structure during the knitting or weaving process;
Lamination	Laminating Layers of Fabric: Sandwiching electronic components between layers of fabric using adhesives or heat-activated films;
Snap Fasteners or Fabric Fasteners	Conductive Snaps: Connecting electronic modules with conductive snaps or fasteners; Snap Fastener Attachments: Attaching electronic components to the fabric using snap fasteners;
3D Printing	3D Printed Components: Creating three-dimensional structures, such as buttons or housings, using flexible materials; 3D Printing Directly onto Fabric: Experimenting with 3D printing techniques directly on fabric;
Wearable Modules	Modular Components: Developing modular electronic components that can be easily attached or detached from the clothing; Pocket or Pouch Integration: Creating pockets or pouches within the clothing to house electronic devices;

Zippers or Fasteners	Conductive Zippers: Using zippers with conductive elements to connect electronic modules; Integrated Fasteners: Sewing or attaching electronic components directly to the fabric using zippers or fasteners;
Fabric Coatings	Conductive Coatings: Applying conductive coatings to the fabric to enable connectivity; Waterproof Coatings: Protecting electronic components with water-resistant or waterproof coatings;
Wire Management	Concealed Wiring: Hiding wiring within seams or fabric layers to maintain a clean and streamlined appearance; Cable Channels: Creating channels within the fabric to route and protect wiring;
Encapsulation	Encapsulating Components: Protecting electronic modules with water-resistant or shock-absorbing materials;
Soft Electronics	Soft and Stretchable Electronics: Designing electronics that are inherently flexible and can conform to the shape of the body;

Source: Author (2024) based on O'Nascimento (2020).

According to Chen and Shih (2014), smart clothing presented an specific evolution process of structure and functions that can be divided into 4 generations: the first of which is based on connecting electrical devices to clothing; the second generation is based on built-in sensors; the third is characterized by the incorporation of sensor capabilities directly into the tissue; the fourth generation, which is currently under development, aims to use devices that blend perfectly and imperceptibly with clothing, depending on the integration method selected for the fourth generation, it can make it difficult to separate the technology from the clothing itself, once it aims to integrate the technology seamlessly (see Figure 2).

Figure 2: 4 generations of smart clothing

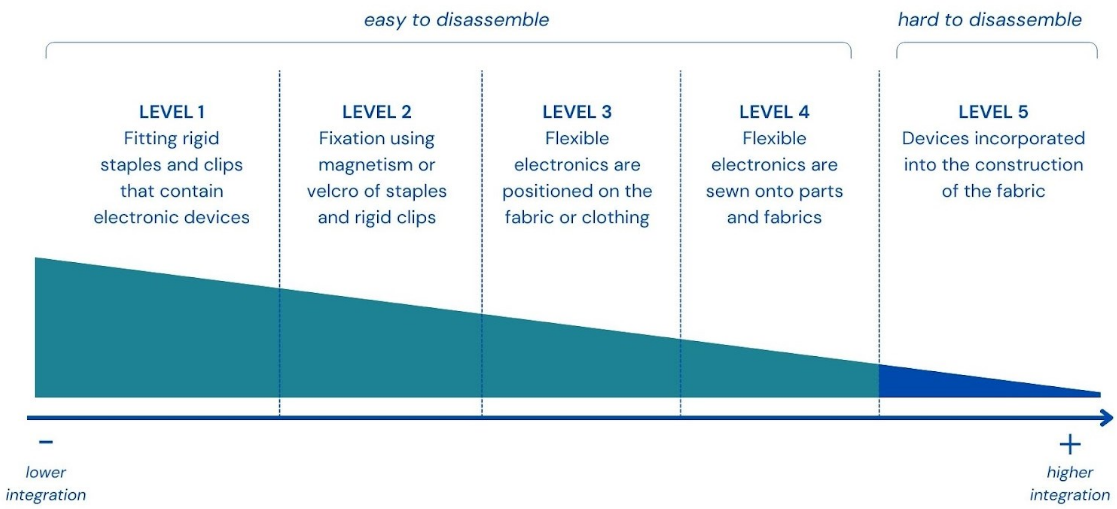


Source: The author (2024) based on Chen and Shih (2014)

Chen and Shih´s (2014) smart clothing generation model can be related to Jiang´s et al. (2021) levels of device integration into clothing, which in turn is based on Matilla (2001). The author points out that the lowest level of integration is the application of rigid staples and clips that contain electronic devices to clothing. Next, the author presents fixing rigid staples and clips using magnetism or velcro. Third, the flexible electronics are positioned on the fabric or clothing. In the fourth level, flexible electronics are sewn onto the pieces and fabrics, unlike the third level, in which electronic components, such as sensors and conductors, are incorporated into the construction of the fabric used to make the piece, and may have some strategic devices just positioned on the tissue, as energy sources (Jiang et al. 2021).

Such characterizations of levels and generations of smart clothing (see Figure 3) can be used as a way to support the study regarding electronic waste from this type of product, as it is directly related to the way in which clothing is incorporated with electronic technology and the difficulty in waste management.

Figure 3: Levels of technology integration to fabric and clothing

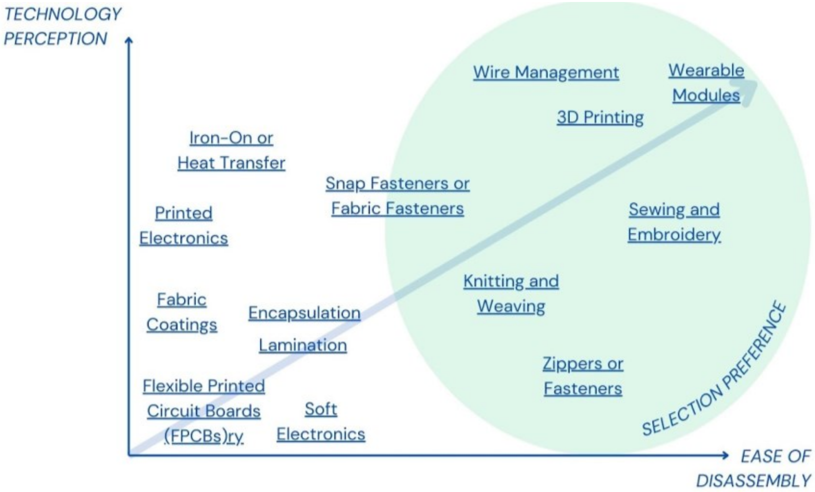


Source: Author (2024) base in Jiang et al. (2021) and Chen and Shih (2014)

In general, the most prominent component in clothing is the fabric itself. What will differ between conventional clothing and smart clothing is the approach for integrating electro-electronic technology, the type of devices used and their positions in the clothes. In this context, it is necessary to keep the attention on textile and its environmental impacts to comprehend all the product characteristics and life cycle. Also, the textile and trims choice need to combine with the e-technology choices on issues such as washability, durability, ease of maintenance, repairability and recyclability, to guarantee that the product will not have problems between the fabric and technological devices. Problems like lower durability of the textile can lead to early disposal of smart clothing. Both materials and electronic devices need to be selected by the same selection criteria and sustainability requirements in an integrated way, hence, the end-of-life solutions for these products need to be selected and formulated in an integrated way.

These issues concerning combination methods and their results in smart clothing washability, durability, ease of maintenance, repairability and recyclability, ease of assembling and disassembling are shown in the figure 4 as a decision guide for the integration approach based on these criteria.

Figure 4: Decision guide for combination methods



Source: The author (2024)

In the design for the smart clothing end-of-life context, figure 2.10 shows that the preference for combination methods selection is related to the technology perception and ease of disassembly. The more noticeable the technology, or more the technology perception, the greater the possibility of disassembly, that way the highlighted combination methods are wearable modules, wire management, 3D printing, sewing and embroidering, knitting and weaving, zippers and fasteners, and snap fasteners and fabric fasteners. Combination methods such as Flexible Printed Circuit Boards (FPCBs) and fabric coatings are not recommended when it comes to a smart clothing possible to disassemble, because of their low technology perception and difficulty to dismount.

4. Discussions on smart clothing structures and EoL

The results of this study highlight the complexity of integrating electronic components into textiles and the challenges associated with smart clothing, particularly regarding end-of-life considerations. The different levels of integration (Jiang et al., 2021) and the evolution of smart clothing generations (Chen & Shih, 2014) demonstrate that the design and production choices directly impact the ease of disassembly and, consequently, the product's environmental performance.

The classification of smart clothing based on its technological integration shows that different approaches, such as perceived technology and seamless technology, require distinct considerations regarding disassembly and recyclability. Seamless technology, where electronics are embedded directly into the textile structure, requires greater attention to material selection and integration methods to facilitate disassembly without compromising the fabric or the electronic components. On the other hand, perceived technology, which often relies on modular or externally attached solutions, may offer more straightforward separation of components, but still requires design strategies that ensure repairability and durability (Kohler, 2013).

The decision guide proposed in this study (Figure 4) provides a strategic approach for designers to select combination methods that align with sustainability principles while maintaining product functionality and durability. The findings confirm that material selection, particularly for electronic components, should be made considering factors such as durability, washability, and reparability to prevent premature disposal. Electro-electronic components embedded into fabrics require specific disassembly strategies, reinforcing the need for design approaches that support circularity, such as Design for Disassembly (DfD) and Design for End-of-Life (DfEoL).

The analysis also suggests that the use of standardized modular components and open-source electronics can enhance product longevity and reusability. This reinforces the importance of considering smart clothing as an interconnected system rather than a mere combination of textiles and electronic devices.

5. Final Considerations

This study explored the state of the art in hardware, structures, and production technologies in smart clothing, emphasizing their implications for end-of-life management. The findings suggest that the integration method plays a crucial role in determining the environmental impact of smart clothing. While different approaches, such as perceived technology and seamless technology, provide unique advantages, they also require specific design considerations to optimize durability, maintenance, and disassembly. In seamless technology, for instance, special attention is needed to ensure that embedded electronics can be efficiently disassembled without damaging textile or functional components.

The research also highlights the importance of adopting an integrated material selection approach, where both textile and electronic components are evaluated under the same sustainability criteria. By implementing strategies such as modular electronics, Design for Disassembly, and the use of standardized interfaces, it is possible to extend the lifecycle of smart garments and minimize e-waste.

Future studies should further investigate scalable disassembly solutions for smart clothing, as well as alternative recycling pathways for electronic textiles. Additionally, research on biodegradable or self-decomposing electronic components could offer new perspectives for sustainable smart clothing design.

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