Circular design options for wearables integrated sportswear to be employed in adverse outdoor conditions

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Abstract: The fashion industry is increasingly committed in improving the sustainability and circularity of its products in a perspective strongly oriented towards technological innovation. To meet these goals, several strategies are used, mainly focusing on product design and production processes. The study of materials suitable for reuse and recycle, the "design for disassembly" of garments, the setup of reverse supply chain to recover the products, and the raising of consumers' awareness and involvement are some of the most challenging strategies. In this perspective, smart textiles and wearable technologies put together the issues of both the fashion and electronic industry, through a wide range of possible integration strategies, increasing the complexity of the circular system to be designed. Sportswear represents an ideal context to develop wearable technologies, having a target of customers interested in technological innovations and willing to spend more efforts for increasing their performances and safety. Starting from an in-depth analysis of the available literature on the topic, this study aims at analyzing and discussing the possible design strategies for the development of circular wearable technologies, presenting a brief case study on the integration of wearables into a sport shirt, specially designed to increase cyclists and runners' safety, including athletes with disability, in adverse environmental conditions. The various options are discussed taking into account the different stakeholders' view, namely the technology developers, the electronic and fashion manufacturers, the fashion retailers and the end users' needs and objectives. Lastly, an application framework to support the industrialization of the considered smart apparels is presented, providing useful hints to increase the circularity of both smart garments and wearable devices.

Keywords: Wearable technologies, circular design review, design-for-disassembly, fashion industry, safety.

1.Introduction

In recent years, the demand for wearable technologies is increasing worldwide (Cientifica, 2016; Statista Research Department, 2021) and, among the available technologies, smart textiles products, such as shirts, pants and jackets, are having a growing attention in the sport sector (Laufer et al, 2018), mainly thanks to their potential to prepare, perform and approach athletes' experience during sports (Memarian *et al.*, 2019). The design and production of these very special clothes must be carefully evaluated considering the great diversity among its basic components: the textile, the electronic devices (sensors, actuators, interconnections and the power supply) and the case for the electronic components (Ramakrishna and Yousefzadeh, 2017). Moreover, smart clothes, combining textile and ICT technologies, poses new challenges in terms of waste streams. The small e-waste items deriving from smart textile can be thrown into unsorted household waste (Köhler, Hilty and Bakker, 2011) and, on the other hand, both textile and e-waste management issues give rise to environmental and human health concerns (Bakhiyi *et al.*, 2018; Butturi *et al.*, 2020; Shirvanimoghaddam *et al.*, 2020).

So, several strategies to increase the sustainability and circularity of smart textile products are under development, in addition to efforts aimed at improving the aesthetics and functionality (Ellen MacArthur Foundation, 2017), in line with the commitment of the fashion industry and the potential long-term risks that the scientific community is raising. In fact, it is demonstrated that the magnitude of risks depends on product design, circumstances of use, and the destination of products at the end of their useful lives (Köhler and Son, 2014). In this context, also the absence of specific regulations and standards for wearable textile for sportswear must be taken in account.

Starting from an in-depth analysis of the available literature, this study aims at analyzing the most suitable circular design strategies that can be applied to a sport shirt specially designed to increase cyclists and runners' safety. The shirt, under development as part of the project WE LIGHT funded by the European Regional Development Fund-Regional Operative Program of the Emilia Romagna Region, integrates wearable technologies designed to increase the visibility of the athletes in adverse environmental conditions. Cycling and running are very popular sports, familiar with high probability of injuries due to accidents. For these sports wearable textiles could help to improve athletic personal comfort, protection, and performance due to the fact that clothes are in general good candidates to be adapted to the needs of the wearer. In particular, they can be employed to control body activity or the environmental conditions around the athlete resulting in a better sport experience. All of these wearables' parts must be at the same time reliable in time, flexible and comfortable. In addition, the intelligence integration into clothes creates many new opportunities, including a network of devices and sensors integrated into clothes and connected to the internet for effective data communication to transfer signals from wearable sensors.

With a view to industrialization of the smart garment under development, this study aims at providing a framework for supporting the integration of circularity options in the smart shirt supply chain.

In general, sustainable product design applies the eco-design principles involving the materials' selection, that should be biodegradable or technical materials with the potential to be safely reused, and the design for disassembly strategy to facilitate the product (or product's components) maintenance, repairability and reuse. The implementation of closed-loop supply chains requires, in addition to sustainable product design, changes in the business models and in the configuration of the supply chains. The circularity-driven approach to the field of smart sportswear is mostly interdisciplinary across product design and ergonomics; materials, environmental and management engineering; chemistry; sensor technologies and wireless networking. Our approach analyses some aspects, identified by the project's participants as key issues to approach the WE LIGHT smart shirt circularity at project level: the circular design options, the materials suitable for reuse and recycling and the status of the regulatory standards. Lastly, the closed-loop supply chain schemes and the role of customers is discussed.

2.Literature review

Improving the circularity of goods, including both electronic and textile products, is recognized as a main objective of the new EU policy, European Green Deal (Commission, 2020). Within the circular framework originally developed by the EMF (Ellen MacArthur Foundation, 2015), some key circular strategies can be identified, including sustainable product design and materials, and closed- loop supply chains (Mendoza *et al.*, 2017).

2.1 Approaches to circular products design in smart textile

Through responsible eco-design, designers have a key role in reducing the life cycle environmental impact of wearable smart textile devices (van der Velden *et al.*, 2015) and in ensuring wearables circularity options (Ellen MacArthur Foundation, 2020). Several eco-design strategies are viable, as design for recycling with zero-waste approaches, disassembly (Claxton and Kent, 2020) or re-use.

Designers can firstly encourage repair and re-use amongst consumers and follow recycle and upcycle design approaches. They should consider aspects such as material flow, the best available technologies, and product longevity (Kozlowski, Searcy and Bardecki, 2018). Secondly the smart recycling approach must be evaluated. Textile can be recycled through different processes (mechanical, chemical and thermal), depending on the recoverability of materials and the level of disassembly, in up- or down-cycling processes, to manufacture the same or different products (Shirvanimoghaddam *et al.*, 2020). The recovery of textile waste as feedstock for new textile applications is limited by the fibers' degradation (plastic fibers can be recycled 7-9 times), the processing costs and impacts, due to the used chemicals. The down-cycling of the textile fibers as reinforced composites for building applications is a viable route for recycling them (Echeverria *et al.*, 2019). The recycle is often restricted by the use of different materials and of laser-based finishing techniques, as well as by the lack of traceability (Cai and Choi, 2020), while the adoption of mono-material enables efficient recovery with minimum waste (Earley and Goldsworthy, 2018). Barriers also exist to integrate the recycled yarns and other materials back into the production chain (Payne, 2015). Though the integration of electronics with textile is becoming more and more sophisticated, it can limit the products' repairability so reducing its longevity; these issues can be addressed through modular design including removable parts (basically the electronic devices that cannot be washed), and providing consumer support, for instance the proper washing and disassembling instructions (Hardy, Wickenden and McLaren, 2020).

The disassembly strategy appears to be one of the most interesting, both during use but also to promote circularity, fostering components and materials recovery. Some accessory parts of garments, such as push-buttons, Velcro strips and pockets, can be used for integrating miniaturized electronics devices minimizing the disassembly time. The Jacquard™ by Google (Google, JacquardTM) was initially attached to a jacket cuff incorporating threads woven into the fabric to create a sensor; to overcome both washing and repairability limits, in its final version Jacquard™ is a removable device that can be located in jacket sleeves or in shoe soles, providing digital connectivity. This second version allows both an easy customization and a standard consumer home washing (Hardy, Wickenden and McLaren, 2020).

Advanced technologies, involving the printing of organic thin-layer e-circuits on fabric surfaces using binders sensitive to microwaves can allow automatic and rapid dismantling of post-consumer smart textiles (Köhler, 2013).

2.2 Materials for smart textile in sportswear

Conventional textiles in sportswear are based on synthetic organic material such as polyamide, polypropylene, polyurethane, polyethylene and commercial derivates of these (such as Nylon, Lycra, Elastane, etc..). Finishing technologies can be applied to provide special properties to the wearable such as anti-odor, antibacterial, breathability, thermal insulation, protection against friction with the skin, thereafter, improving durability and comfort. Synthetic fibers are favorable with respect to natural ones, such as cotton, silk or wool, because of their lower weight and price and easier industrial processability.

In Table 1 the main properties of different types of fibers suitable for sportswear has been shown. Among these the most employed one are polyamide and polypropylene due to their easier processability**.** The use of eco-friendly and renewable raw materials in textile is still a key challenge: although recycled materials, e.g. polyester/nylon from bottle, are currently used for manufacturing of textiles, the recycling of fabrics from old garments into new fabrics is hardly feasible (Islam, Perry and Gill, 2020).

Table 1: Comparison among textile materials suitable for sportswear (Bonetti, Ferruccio, Dotti, 2012)

Materials	Density (g/cm^3)	Elongation (%)	Cost (€/Kg)
Polyamide	1.14	90	2.26
Polypropylene	0.95	100	1.43
Polyurethane	1.05	600	1.85
Polyethylene	0.92	200	1.47
Cotton	1.54	7	1.46

Metals incorporated into textile materials to obtain electrical conductivity have been in the market for several years (Latifi, Payvandi, & Yousfzadeh, 2010). However, although metallic fibers have some advantages such as availability, high electrical conductivity, they are heavier and stiffer than most textile fibers and are brittle and not flexible enough, making the product uncomfortable for sportswear. Moreover, when considering smart textile recycling and disposal, the presence of metals has higher environmental impacts (Köhler, Hilty and Bakker, 2011).

Indeed, organic semiconducting materials, such as transistors and light emission diode (LED) coupled with optical fibers have been considered for developing wearables due to their good electronic conductivity and mechanical properties. In fact, LED can serve as light source for glass or polymeric optical fibers, suitable for seamless textile integration with industrial processes, due to their restrained diameters (up to microns range). Various examples of electronic textiles for lighting are available, involving the use one of fiber optics, LED strips, electroluminescent wires and lasers (Hardy *et al.*, 2018), with different functionalities and limits. LED technology has a lot to offer in protection of the wearer, as it can be employed for lightning or illuminating textiles. The first concept was developed by France Telecom in cooperation with ENSAIT in order to emit light in designed areas of a shirt by damaging the cladding layer of the optical fibers as this causes the light to be emitted (Jayaraman, S., Kiekens, P., Grancaric, 2006). A second generation of shirt involved attached or built-in LEDs that are stretchable and fully washable, but in this case the final application was meant for leisure (ColorKinetics, 2020; Cutecircuit, 2019). The latest development includes the construction of textile-based light-emitting materials but with critical issues concerning the end life of the products (Mohring, 2011).

Not only sensors and actuators integration should be carefully considered during the design of a smart textile for sportswear but also batteries to supply power to the electronic components and communication devices (Bocchetta *et al.*, 2020). Again, the requirement for sportswear asks for flexible energy-saving devices, with low self-discharging and environment-friendly as they need to be replaced or recharged after a while. Consequently, the demand for flexible energy harvesters that are compatible with clothes has increased. With this intent flexible lithium-ion based batteries have been developed by using materials such as carbon/polymer composite (Song *et al.*, 2018) and graphene (Chen *et al.*, 2018). Supercapacitors are another potential candidate due to their high-power density and stable cycling life, nevertheless, improvements are needed to enhance their energy density (Ko *et al.*, 2017).

Beside stretching and washing stresses, sports clothing is also subject to sweating, so the protection of electronics and interconnections is necessary. The encapsulating technique of all the electronics devices into the textile plays a major role for the design of the final products, as it can be achieved with several different methods (Köhler, Hilty and Bakker, 2011). The embedding of the electronics by molding or gluing of the board and sensors should both mechanically protect the electronics and also protect it from water penetration during the washing process, but these conventional techniques arise concerns about the environmental impact due to glue employment and to the final product disposal. Case designs and constructions are driven by several variables: aesthetics, specific end-use application/performance, and production cost criteria. For safety reasons, this case should also consider mechanisms for impact mitigation, as a rigid outer shell should absorb impact energy by deflecting and spreading the impact over a larger area. At the same time the thickness of material employed should be comfortable enough for the athletes (e.g., lighter) but avoiding the breaking of it due to a possible impact. Regardless cost generally an injection-molded, semirigid polymer (e.g., polycarbonate, acrylonitrile-butadiene-styrene, polyolefins) can be considered to keep lower prices, but also a 3D printing technique can be considered to improve the aesthetic and comfort requirements. Some relative selected properties associated with possible case material performance and selection criteria are summarized in Table 2. From this it is clear that polycarbonate offers the highest level of energy absorption and impact resistance and, thus, can be employed in higher price-point products.

High-impact modified ABS resins can be used for general and medium-impact applications, whereas lower-cost general-purpose protection can be given from polyethylene or polypropylene materials. In addition, to improve the fit with athletes' body and the products ergonomic standards, resilient foams, such as polyurethane (PU), can be thought of as energy-absorbing springs in the part of the case in contact with the body of the wearer.

Table 2. Relative performance selection for electronic device case

Materials	Impact Strength	Dimensional Stability	Cost
Polycarbonate	High	High	High
ABS	Med-High	High	Med
Polypropylene	Low-Med	Med-Low	Low
Polyethylene	Low	Low	Low

2.3 Closed-loop supply chain

The research on closed-loop supply chain (CLSC) and its applications is very popular in the textile industry. CLSC creates an interconnected system where the collaboration among the stakeholders can improve the sustainability of products, since, for instance, the recycling strategies affect both the design and the use stage, and the product design determines the materials' recyclability (Fung *et al.*, 2021). CLCS can involve clothes re-use or rental, as well as recycling paths through reverse supply chains requiring cooperation and commitments from fashion manufacturers and retailers and the consumers (Cai and Choi, 2020).

Reverse logistic (or supply chain) is defined as the set of activities needed to recover products from the market and to move them back from the consumer to the retailer or the manufacturer (Dissanayake and Sinha, 2015). The process, when used with the aim to recycle, repair or remanufacturing returned and secondary goods, led to virtuous processes of circular economy and environmental sustainability (Guo et al, 2020). Through the reverse logistic approach, the returned wasted fashion products increase their value as they can be resold to other markets or recycled in a sustainable way. Two kinds of reverse logistics can occur: one refers to the return policy between retailers and suppliers, while the other involves consumers and retailers, with good results in terms of consumers' participation and customers' loyalty improving (Yang, Song and Tong, 2017).

It is not by chance that several take-back schemes have been implemented by sportswear firms in the last years (Figure 1). For instance, Napapijri have launched the Circular Series, a fully circular collection whose products are, not only made from a mono-material composition allowing the transformation into new fabric, but also linked to a take-back program that allows customers to return them to Napapijri after two years from purchase and to receive a 20% discount on the next purchase (Cradle to Cradle Products Innovation Institute, 2021; Napapijri Circular Series, 2021). The development of those kinds of activities engages customers, and other stakeholders in new behaviors and patterns of responsibility and influence environmental and circular policies (Corvellec and Stålb, 2019). This is an important issue, considering the lack of regulations.

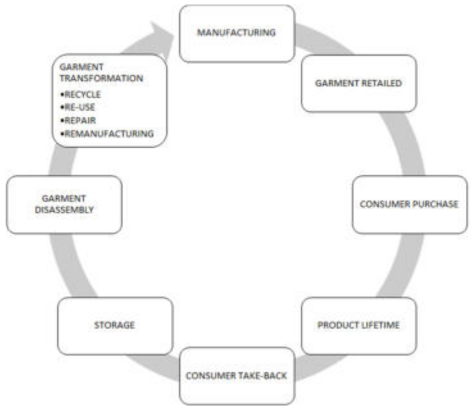

Figure 1: Reverse logistics system for fashion remanufacturing. Adaptation from Dissanayake and Sinha (2015) and Napapijri Circular Series (2021)

Regarding the smart textile, the fashion supply-chain take-back systems, when existing, are not designed for dealing with both textile and electronics, nor the established electronic waste recycling systems are equipped for dismantling and treating smart textile. Automated equipment is not designed to separate textile fibers and electronics components (Köhler, Hilty and Bakker, 2011).

2.4 Customers role in the fashion circularity approach

Integrated environmental and stakeholder analysis demonstrated that one of the most important links of a sustainable supply chain is the customer, considering that some of the largest environmental impacts of a garment are during the use and end-of-life phases (Kozlowski *et al.*, 2012). The customer's needs could influence the concept and the design of a garment and, moreover, their behavior can affect the overall environmental profile, as well as circular economy practices (Roos et al, 2016). For instance, customer's care processes, such as washing and ironing, could limit maintenance and cause irreversible damage to electronic components hindering repairability and re-use practices (Hardy *et al.*, 2020).

On the other hand, the increased customers' awareness on sustainable practices can favor the purchase of products with minimum impact on environment and society, and the subsequent disposal behavior (Mostaghel and Chirumalla, 2021). According to Fung *et al.* (2021) the labelling of the garments directly affects the users' recycling and reuse habits. Unless otherwise indicated on the label, smart textile is discarded with old-clothes rather than as e-waste (Köhler, Hilty and Bakker, 2011).

Discarding clothing may be due to the lack of information about possible pathways for recycling, so, beside the proper infrastructure, better communication flows between textile producers and recyclers, advertised take-back programs and consumers' engagement can improve the textile recycling rate (Paço *et al.*, 2021).

2.5 Standards

While there have been many advances to improve smart textiles technical performances as sportswear, the commercial growth of this market is strongly limited by the lack of technical specifications and regulatory standards needed for manufacturing, maintenance and disposal at the end life of such equipment (Veske and Ilén, 2020). International standardization and interoperability are two conditions that are often regulated by international rules that do not currently exist in this field (Fulton *et al.*, 2018). The ISO/TR 23383:2020 provides definitions in the field of "smart" textiles and textile products as well as a categorization of different types of smart textiles. It describes briefly the current stage of development of these products and their application potential and gives indications on preferential standardization needs. One of the major causes of the lack of standardization of smart textiles is the strong difference among their different components (textile, electronic, encapsulation, lighting device). In fact, the repeated washing and drying of textile has been known to have a detrimental impact on both aesthetics and technical performance (Slater, 1991). Therefore, manufacturers need to provide instructions on cleaning, and standards organizations have published detailed guidelines for cleaning and maintenance. Moreover, labelling should inform on the locations and functions of the integrated electronics, provide warranty and take-back schemes information, and support the recycling operators, helping them in sorting smart apparel from conventional clothing (Köhler, 2013; Hardy, Wickenden and McLaren, 2020).

3. WE LIGHT smart shirt device prototypes development

WE LIGHT is an industrial research project, that aims at designing and developing some prototypes of sportswear integrated with electronic, optical and sensor technology systems capable of connecting the athletes with the external environment. During the first project phase, prototypes' design and manufacturing strategies employed in WE LIGHT have considered the most recent technological innovation both for textile fabrication and for electronics integration in an environmental sustainability perspective.

In the context of textiles for sportswear (Table 1) polyamide-based materials have been preferred due to its high versatility in terms of manufacturing technology and coupling with other plastic derived components. In addition, it must be noted that polyamide-based fibers are particularly favorable to be painted and, thereafter, to promote the versatility of the shirt from an aesthetic point of view. For textile fabrication seamless technology has been taken into account for WE LIGHT: as a native procedure for underwear due to its extremely low weight and enhanced wearability, it could be proposed for sportswear where athletes comfort is one of the main driven issues. Seamless textile is generally characterized by a minimal employment of seam, leading to a restrained skin abrasion, and by the coupling of two light fabrics that ensure the respect of the skin balances of breathability and permeability, as well as protection from atmospheric agents (Soldati and Sabbioni, 2012). A tailored case for the electronics has been considered, as it is easy to remove from the textile and as it can be manufactured specifically for the wearer body. This case has been specifically designed to contain only the electronic devices needed and to be applied in the back of the shirt. This position has been carefully studied considering the most suitable body position for this type of device during cycling or running, promoting its visibility but avoiding possible injuries due to falls and consequently devices' crash. Considering the design for electronics encapsulation, materials such as Polycarbonate, ABS, Polypropylene and Polyethylene (Table 2) can be shaped through additive manufacturing (AM). In fact, the principal benefits for AM technology are the possibility to quickly change the design promoting a strong design customization and reducing the set-up time during production. In addition, AM allows products to be optimized for function and specific customer needs reducing wastes (Holmström *et al.*, 2010). In the context of smart textile design AM is capable of customizing and optimizing the case shape and dimension according to the desired customer demand, rather than being restricted by production technology or supply-chain constraints. The electronics include a wireless communication device and light sensors to control the LED switch on.

4. Circular design strategies for the WE LIGHT smart shirt

The collected circular design options for the supply chain of wearable integrated sportswear, listed in the Table 3, will be presented to designers and manufacturers involved in the project during the phase concerning the WE LIGHT smart shirt industrialization analysis.

Considering the materials, the use of recyclable textile option will be discussed both in terms of the environmental impacts and the availability of a regional recovery chain. Beside the use of more sustainable textile materials, a cutting-edge option is the use of recyclable materials in additive manufacturing. More sustainable formulations can be obtained by mixing the technopolymer (or thermosetting) matrix with percentages of bio components, maintaining high mechanical performance (Barbi *et al.*, 2021).

As far as concerns the global design, the design for disassembly approach will be proposed, such as the use of alternative electronics devices (such as flexible circuits), the analysis of different positions for the removable devices, and the labelling with disassembling instructions to support consumers and recyclers. Groups of athletes, that will test the shirt performance and the device positioning in relation to unobtrusively areas (Ferraro and Ingaramo, 2015), will be asked to evaluate some re-use and customization options: the size customization of the wearables, the multi-functional or shared use of the shirt, and the possibility of upgrading the electronics devices. The discussion of recovery and take-back schemes will involve all the stakeholders along the supply chain at the regional level, including the retailers and the recyclers.

Table 3. Circular design strategies for wearables integrated sportswear

Approach	Circular strategy	Option	Main stakeholder
Product design - materials	Recycling Remanufac turing	re/up-recyclable materials	designer, manufacturer
Product design – design for disassembly	Repair Re-use Recycling	removable devices positioning, flexible e-circuits, labelling	designer, manufacturer, consumer, recycler
CLSC	Re-use Recycling	recovery and take-back schemes, labelling	manufacturer, retailer, consumer, recycler
Customer Engagement	Re-use	multi-functional use, customization repairable, replaceable, or upgradable devices	designer, consumer, retailer

5. Conclusions

This paper presents an analysis of the circularity strategies that can be applied to the supply chain of a sport shirts integrating wearable technologies, designed to increase athletes' safety within the WE LIGHT project. The reviewed literature emphasized the complexity of combining textile and electronics, both at the design and recovery level. The solutions adopted by researchers at the prototype development level are described and the main viable and most suitable circularity options for the case study under analysis, as emerged from literature, are presented. The further steps of the presented research will include the analysis of the stakeholders' evaluations combined with the assessment of the environmental impacts of the preferred options, performed in lifecycle perspective. In conclusion, the overall aim is to maximize all the feasible circular strategies in order to realize a virtuous supply chain able to minimize the environmental impacts.

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