Smart Textiles and Clothing: An Opportunity or a Threat for Sustainability?

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Wearable technology products which include smart clothing and textiles have grown in popularity and are only expected to become more ubiquitous over the next several years with an annual growth of 23 percent reaching $100 billion in sales by 2023 and $150 billion by 2026. But this growing demand does not come without considerable cost. Combining electronics and textiles, which both are relatively short-lived mass consumer goods, would intensify product obsolescence and lead to even shorter life cycles and abandonment of products. Although there is extensive research on the sustainability of fashion, limited research exists on the sustainability of smart textiles and clothing, and it appears timely and significant for an exploratory study on this topic. This study explores sustainability of smart textiles and clothing by a critical and in-depth review of existing literature and recent design efforts in the industry and in alternative realms such as maker spaces. The study introduces design approaches for more sustainable products and user experiences by employing Norman's levels of emotional design [1], and Lamb and Kallal's functional, expressive, and aesthetic (FEA) apparel design models [2] as grounding frameworks to discuss the sustainability of smart textiles and clothing from all angles.

Additional Key Words and Phrases: smart textiles, smart clothing, sustainability, product attachment

1 INTRODUCTION

The global textile and clothing industry is going through a transformation as a result of technological progress and sustainability concerns [3]. Wearable technology as well as the integration of technology into textiles and clothing continues to expand in the academic literature and in the industry, which will likely to lead into new and more products in the long term. Both the textiles and the micro-electronics industries have already introduced many environmental and social problems; and the popularity of wearable technologies only compound the issue by introducing harder-to-recycle components into textiles with built-in electronic functions. This section will provide background information about the sustainability concerns and opportunities for smart textiles and clothing from the perspectives of materials and product lifecycles, user behavior, and socio cultural and ethical considerations.

1.1 Materials and Product Lifecycle

Wearable technology has been defined and interpreted in a variety of ways in the literature. Dunne defines it from a broad perspective as "body mounted technology" that can come in forms of accessories, clothing and computers worn on the human body [4]. A more specific subgroup of wearable technology, smart clothing or interactive clothing, can be distinguished from other worn accessories such as bracelets and watches. In this specific subgroup, electronic textiles (e-textiles) or smart textiles become the building blocks of smart clothing, referring to fibers, yarns or fabrics with embedded electronic functions that offer flexibility that is not existing in traditional electronics [5]. Electrical functions can be embedded into textiles through a variety of methods, including sewing, weaving, knitting, embroidery, coating, laminating, printing, braiding and chemical treatments [5]. According to Kohler, there are multiple levels into which electrical functions can be embedded into textiles [6]. The lowest level of integration is defined as *Adoption,* where textiles serve as a platform to contain electronic devices such as the watch-pockets on jeans (introduced by Levi's in 1903) or pockets for smart phones and earphones [6]. The second level introduced by Kohler is *Integration,* which includes the well-known, traditional textile manufacturing methods of embroidering, knitting or printing of electrically conductive materials [6]. The third level called *Combination* refers to textile materials with inherent electrical characteristics such as yarn transistors or photovoltaic fibers [6].

The combination of electronic technologies with textile materials and the level of integration between them result in new challenges for sustainability and disrupt the recycling process of traditional textile materials [7-8]. Raw materials such as cotton and polyester already cause environmental risks as a result of excessive use of water, pesticides and chemical treatments, and disposability. Combining these materials and electronics that may contain scarce raw materials, heavy metals and toxic chemicals compound the environmental risks for smart textiles and clothing. Smart textiles and clothing also rely on conventional power supplies like short-lived batteries that are hard to recycle [9]. Especially for smart textile materials

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DOI: https://doi.org/ 10.17028/rd.lboro.9724619

with inherent and integrated electrical characteristics, such as conductive polyamide or nylon yarn coated with silver or copper metal depositions, it is not possible to remove and reuse electrical parts, nor to mechanically recycle these metal parts [7]. Textile materials with electrical properties are widely employed in smart clothing design in addition to commercially available cables, miniaturized electronic components, sensors and connectors [5]. Ossevoort reports that an average electronic device may contain many different components in very small quantities and therefore can only be recycled by shredding the product into smaller pieces rather than separating them down to basic materials [7]. Therefore, combining textiles in any form with electronic devices adds new, unprecedent challenges from an environmental point of view.

In addition to the consequences of materials on sustainability, the rapid temporal cycles of current technology, associated with the term "techno trash" [10], have profound environmental impacts when doubled with the conspicuous consumption in fashion. The idea of embedding digital technology into fashion has been a popular creative exploration for designers. There have been countless iterations of one-off dresses or accessories that would light up for aesthetic purposes or based on internal or environmental stimuli. These approaches have been criticized for the degree of technology integrated into clothing for the sake of technology that has never make it to the market. For those digital technologies integrated clothing that have made it to the market, they are prone to technology obsolescence; as the technology progresses, they are replaced with new versions with new features and technological capabilities. Therefore, the sustainability of smart textiles requires a systems-thinking approach and depends on the sustainability of its constituent components as well as the lifespan of the clothes/wearables to which the technology is converted over time.

Recently, the rising sustainability concerns regarding smart textiles and clothing have started alternative material explorations around the issue in research and practitioner communities. Aniela Hoitink has been experimenting with Mycelium, the roots of mushrooms, to develop sustainable and bio-based alternative to traditional textiles. These explorations have been extended into combining conductive materials and technology into the bio degradable MycoTex fabric grown from Mycelium [11]. Ecovative Design holds a patent for growing electrically conductive tissue comprised of a sheet of Mycelium with a wiring pattern for an electrical circuit [12]. Audrey Ng studied microbial cellulose, Kombucha textile, and utilized its self-adhesive features during the drying process to allow circuit to self-assemble between the two surfaces of kombucha [13]. BioLogic is another research team in MIT's Tangible Media Group in the Media Lab, growing living actuators and synthesizing responsive bio-skin [14]. Departing from the expansion and contraction behavior of the ancient bacteria Bacillus Subtilis Natt relative to atmospheric moisture, the group developed smart fabric that reacts to body heat and sweat, causing flaps around heat zones to open, enabling sweat to evaporate and hence to cool down the body.

1.2 User Behavior

Research shows that one in ten American adults own some form of wearable technology device, but half of them do not use it [15]. The reasons for abandonment of such products have been depicted as 1) the product did not fit users' conceptions of themselves but rather referred to fit extreme types of users such as athletes or people with health conditions, 2) the data collected by the smart product were not useful, 3) maintenance of the smart product was regarded as too much extra work [15]. Therefore, to improve the product's lifetime, it is important that the product represents more than its functionality. User behavior plays a critical role in determining the sustainability of a product that is beyond physical measures of material characteristics and recyclability. Even though products would be designed according to the highest sustainability standards, the daily interactions of the user with the product can override these efforts. According to Ossevoort, smart textiles and clothing hold the potential to offer a more sustainable option to ordinary textiles if they offer better value for the end user, user attachment and longevity [7]. In order to increase product longevity, users need to feel an emotional attachment towards the products that they own which have a significant effect on postponing product replacement [16]. Therefore, value needs to be placed on stronger 'user-product' attachment which can be accomplished through design, as it provides meaning and offers the possibility to attach oneself to a product [17, 18]. Research shows that around 80% of a product's environmental impact can be eliminated through better design and intentional design [19, 20]. Intentional design is not only about the designing the product but is also about designing the interaction between the user and the product, and therefore about promoting sustainable behaviors in the use of the product throughout its lifecycle [20].

There have been examples of wearable technology and research initiatives that promote sustainable user behavior and design that can serve as role models for smart textiles and clothing. For example, Worldbeing is a wearable made from recycled electronic waste that tracks carbon usage by partnering with databases of existing services for tracking real time purchases, travel, food consumption etc., to empower users to make more sustainable decisions [21]. In addition, The WEAR Sustain project funded under the EU Horizon 2020 Work Programme in 2016-17, has been supporting the development of networks and providing resources for wearable technology, smart textile, and e-textiles sectors, leading to more ethical and sustainable design [22].

1.3 Socio Cultural and Ethical Considerations

On top of environmental risks, smart textile and clothing could pose sociocultural risks that should not be undermined. There are plenty of data privacy and security issues related to the rise of wearable technologies. 52% of wearable technology users state a loss of privacy as their biggest concern [23]. Such technologies could also further intensify an always-online-culture, which could have a harmful impact on genuine human interactions and general wellbeing.

2 THEORETICAL FRAMEWORK

Norman proposes that individuals' experiences of the world and designed objects are influenced at three different, yet interconnected levels: visceral, behavioral and reflective [1]. The visceral level refers to the product appearance and aesthetic appeal to the user. Reactions to the visceral level of design are hardwired, powerful and immediate, as it takes only a few seconds to determine if the 'look and feel' of a product is appealing. The behavioral level refers to functions, performance, and effectiveness of use and usability of a product. The reactions of the behavioral level are about the value individuals derive from the products they use. When interaction during the use of a product is familiar and expected, there is joy and satisfaction associated with that experience and usability of a product. The reflective level of design refers to personal satisfaction and feelings after being immersed in the use experience of a product. A positive reaction to reflective level of design evokes a sense of identity from using a product that extends beyond the product itself. Similar to Norman's framework of emotional design, Lamb and Kallal [2] suggested a specific framework related to clothing design that introduces the three dimensions of functional, expressive, and aesthetic considerations to assess user needs and wants. In this framework the functional dimension relates to utilitarian aspects of clothing such as fit, comfort, and mobility or protection. The expressive dimension of clothing is about the communicative and symbolic aspects of clothing, compatibleness with user's self-identity, and values and meanings associated with clothes. Aesthetic considerations refer to the appearance, cut, proportion, color, fabrics and the overall style of clothing.

Unlike regular textiles and clothing, and regular technological devices, smart textiles and clothing are complex in their simultaneous integration of clothing and electronic characteristics [24]. The following figure summarizes how Norman's and Lamb and Kallal's frameworks relate to each other and provides a framework of combined characteristics applicable to smart textiles & clothing. Product longevity by better user-product attachment can be formed through the three levels of involvement as introduced in this framework.

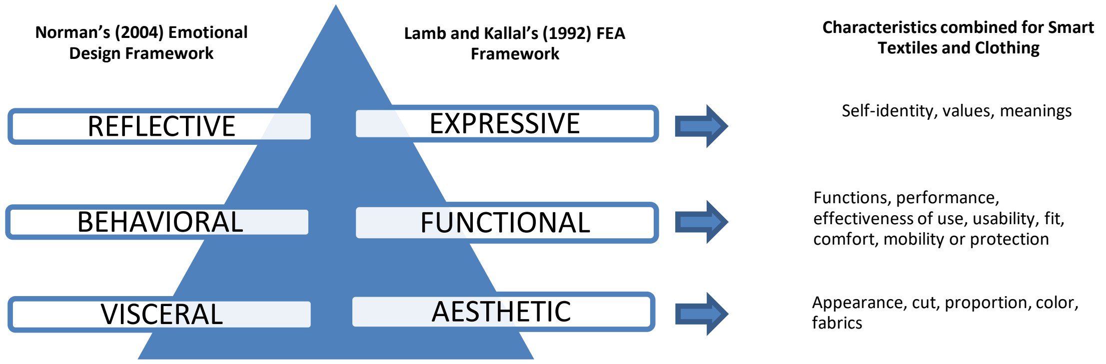

Fig. 1. Three levels of involvement for design of smart textiles and clothing

3 DISCUSSION

3.1 Visceral / Aesthetic Involvement in Smart Textiles and Clothing

Aesthetic or visceral characteristics of design can be discussed from two perspectives in the context of smart textiles and clothing. First, similar to regular clothing they need to satisfy needs with regard to fashion and style [25]. According to a study 53% of users expect wearable technology to be more stylish [23]. Individuals do not want to compromise their fashion sense for using advanced technology and aesthetic factors of color, fabric, cut and proportion; style expectations are highly influential in the acceptability of smart clothing [26, 27]. Second, while smart textiles and clothing should satisfy the needs related to style and aesthetic, they should not drive consumption tied to aesthetic obsolescence, which occurs when fashion changes and something is no longer in style.

Aesthetically pleasing and longer-lasting textiles and clothing that can stand temporary fashion trends become an important strategy of sustainability to promote user-product attachment [28]. Smart textiles and clothing could offer possibilities of updating their appearance through change in color, texture, pattern and even form, reducing the need to constantly purchase a new and up-to-date item. An example of such technology is the E Ink or the Electronic Ink microcapsules laminated onto a film which than can be applied onto any surface including textiles. The E Ink technology also offers an energy efficient alternative to LCD screen displays that rely on significantly high battery power. A start-up company, wearTRBL, proposed a connected T-shirt with an embedded flexible E Ink display in which wearers can upload, change and customize designs and patterns via a mobile app [29]. Similarly, Shiftwear developed a sneaker with colored E Ink that can be customized to display visual designs and videos on the sides of the shoes [30].

Reactive dyes have been used to develop textiles and clothing and that can change visually. The Unseen, a UK-based material innovation company, focuses on the application of reactive dyes that can respond to environmental stimuli by changing color that applies its technology in different contexts via capsule collections and conceptual design collaborations [31]. For example, the company's collaboration with Selfridges has yielded luxury-bag collection that alters its color seasonally or in response to wind, heat and light. Other conceptual applications of the reactive dye technology include a T-shirt that reacts to climate change by changing color.

Shape-memory textiles and clothing have been widely explored to design form or texture-changing clothing as another way of transforming the visual characteristics of fashion products. Shape-memory materials have the ability to remember and return to a previous form after being subject to thermal or magnetic stimuli [32]. Shape-memory alloys (SMA) and shape-memory polymers that belong to a subgroup of shape-memory materials are studied for their application in smart textiles and clothing and are especially integrated into woven textile structures [33].The earliest creative exploration of shape- changing textiles and clothing is by the designer Marielle Leenders, who developed a jacket that would change in hem length and in texture through the response of SMA woven into textile structure to gauge environmental temperature change [34]. Koo, Lin and Zhou experimented with SMA and origami-folding techniques to develop smart clothing with controllable form change in width and length [35]. Similar ideas have been explored in maker communities such as the E-Textile Summer Camp: peer-to-peer led, self-organized gatherings of e-textile and electronic craft practitioners in fashion. The community researched the decorative-stitching-type smocking techniques that allow the shirring of fabric into regularly spaced tucks [36], using SMA wires pre-trained to form smocking textures on the fabric [37].

While these examples range from early experimental explorations to soon-to-be marketable products, they represent the potential of smart clothing and textiles for more sustainable, transformable and customizable products that hold the potential to last aesthetically over time for diverse users.

3.2 Behavioral/ Functional Involvement in Smart Textiles and Clothing

The functions of clothing have evolved from merely providing shelter to the human body for protection, to augmenting and enhancing human capabilities [38]. The functional aspects of smart textiles and clothing are a critical component of use. However, as discussed previously, these functions do not translate into longer lasting user-product attachment, and individuals still abandon using these technologies due to factors that also relate to the behavioral level of design such as the difficulty of maintenance and care of the products and not finding direct application of the data collected in daily life.

Especially for lay users, the maintenance of smart clothing can negatively affect the ease of use and becomes one of the major reasons for unsustainable user behavior. In addition to care and maintenance activities inherent to traditional textiles and clothing like laundry, ironing and repair (i.e., seams, buttons, holes, etc.), new maintenance and care activities and skills are required for smart textiles and clothing. Charging, accessing and/or storing data collected, specialized laundry requirements (i.e., removing hardware component, hand washing) could be examples of new and additional activities for maintenance and care. Levi's® Commuter X Jacquard by Google jacket - which comes with a e-textile based interface where one can change or pause a song or pick up a phone- requires removing of the Jacquard™ snap tag hardware and can only stand up to 10 washes before it loses its interactive abilities and may well leave a wearer with an unusable hardware. In addition, entirely new and more complicated skill sets such as soldering or using basic electrical characterization devices may be required for self-repair of smart textiles and clothing. Specialized and costly maintenance services that may override the cost and benefit of repair are likely to appear for smart textiles and clothing, which in the end could lead to new and more product sales.

The use of smart textiles and clothing may require building new mental models: in other words, new thought processes about how traditional textiles and clothing function in ways that may affect the ease of use and therefore user-product attachment in the long term. Certain smart clothing may need different ways for donning or doffing or other wearing requirements. For example, smart shorts available in the market that track muscle activation from glutes would require direct skin contact and therefore wearing no underwear, or smart socks would require wearing secondary hard components around ankles.

Comfort and fit are other important factors that affect long term user-product attachment. Many smart clothes require close contact with the skin in order to collect data which result in a tighter, compression type of fit that may impede with comfort and body image for different personal physiques. Sizes, locations and numbers of hardware components attached to clothing may also hinder comfort parameters related to mobility.

According to the Technology Acceptance Model (TAM) by Davis, individual's intention to adopt a new technology is affected by the perceived usefulness and perceived ease of use, and the more a "person perceives a technology to be useful, the more the user believes it is easy to use, and the more the user intends to use the technology" [39]. The more benefit smart textiles and clothing could provide for the wearer, the more likely that they will be perceived as easy to use and adopted for longer periods of time. Therefore, smart textiles and clothing that offer specialized, reliable, continuous and useful functions are likely to be perceived as easy to use in the context of the challenges introduced above.

3.3 Reflective/ Expressive Involvement in Smart Textiles and Clothing

The highest tier of design encompasses how a product relates to an individual personally in terms of self-identity, values and meanings. Some literature has critiqued the focus on the practical functionalities of wearable technologies such as smart textiles and clothing, noting that such an approach underrates or ignores their expressive qualities [40]. According to Tamminen & Holmgren wearable products serve reflective level of design in three ways; 1. optimization of the self through enhancing and augmenting the body, 2. formation of larger and connected communities around their function (i.e. sports), 3. "infusing the owner with feelings of familiarity, continuity of identity, sense of true self, reflection" [41]. These authors argue that -as compared to timeless fashion- fast replacement cycles due to the rapid development of new technologies lack the power of being made singular and the possibility of inscribing personal meanings to products that are always connected to other devices. Hence, there are important challenges to the possible sustainability of, and product attachment to, smart textiles and clothing.

On the other hand, some of the technology that especially tracks human conditions embedded in the textiles requires the garment to be customized to the wearer and provides singularity in terms of the functions and the benefits it provides to the wearer. For example, Nadi-X yoga pants integrated sensors and haptic feedback to help to improve yoga poses and provide a personalized feedback to fix posture as an individual is in a pose [42]. Machine-learning technology, or the idea that systems can learn from data and make decision without human intervention, also holds high potential for the customization of smart clothing. For example, researchers at the Harvard BioDesign Lab developed a machine-learning algorithm that can rapidly tailor personalized control strategies for soft, wearable exosuits [43].

Many new smart textiles and clothes also offer customization in terms of their aesthetics as discussed in the "Visceral / Aesthetic Involvement in Smart Textiles and Clothing" section. Smart textiles and clothes that are able to change patterns, colors or display images through computation are interesting examples of how these technologies can be used to create dynamic clothing that add meanings and present self-identity.

4 CONCLUSION

Clothing and textiles are always in close contact with the human body and therefore are perfect realms to gain insight about the wearer and their environment via integrated technologies. Although there are limited numbers of smart clothing that make it to the market, they are regarded as the future of wearable technology, overshadowing smart accessories. Smart textiles and clothing offer comfort and well-known aesthetics and customizability benefits over other non-textile wearables. However, it still is unknown what happens if smart textiles and clothing become the norm and individuals start to own more and more of these products, replacing traditional clothing.

Approaching smart textiles and clothing with the existing models in the fashion system that promotes changing styles could further threaten sustainability. Major threats include increased environmental risks and product abandonment rates. Adding electrical properties to traditional textiles would disrupt the current and established recycling procedures of traditional textiles and would intensify the environmental impact. Additional maintenance and care needs for smart textiles and clothing are found to increase abandonment rates. On the other hand, there exist opportunities to increase product longevity via transformable aesthetics which can update according to changing styles and high functional customization satisfying both the expressive and the specific functional needs of wearers and the environment.

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