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Life cycle assessment and eco-design of smart textiles: The importance of material selection demonstrated through e-textile product redesign

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ABSTRACT

Smart textiles have progressed well beyond the laboratory stage. A growing community of smart textile designers utilises engineered materials and advanced manufacturing technologies to create marketable products. To implement an environmentally conscious way of product innovation, the environmental impact of such products needs to be taken into account already at the early design-stages. A life-cycle perspective on the consequences of design choices can guide the implementation of eco-design measures. However, not much literature is available thus far to empower designers in making sustainable design decisions.

To meet this need, this article presents a life cycle assessment (LCA) of a wearable smart textile device for ambulant medical therapy. The case study focuses on material selection, since this aspect is one of the most relevant choices at the prototyping stage. The eco-cost approach was used to compare the LCA-results of the original prototype design against various eco-redesign options.

The results suggest several priority areas for environmental improvement. One possibility is the replacement of silver based conductive yarns by copper based alternatives. Another finding suggests the use of acryl instead of wool. The case study results are the starting point for further discussion on the role of designers with respect to responsible eco-design.

1. Introduction

1.1. Background and hypothesis

Technological advancement of smart textile materials and manufacturing processes is developing rapidly. New types of materials, technologies and knowledge allow designers to integrate smart solutions on smaller and less visible scales and to obtain results faster than ever before. This offers a lot of opportunities, but raises new questions and concerns as well.

The above developments have led to an enormous variety of smart textile prototypes that have been presented at fairs and exhibitions. The textile sector embraces these innovative ideas as they offer plenty of possibilities for novel products and open up new business opportunities for the textiles and fashion industry [43,50]. Innovations in smart textiles technology promise to add value to the consumer's life and satisfy the textile industry's demand for new market opportunities. Previous innovation cycles, and this concerns the high-tech sector in particular, showed how novel technologies unexpectedly proliferated the daily life of average consumers within a relatively short time. Examples of break-through applications encompass digital watches, mp3-players, smart phones, and tablet PCs. Smart textiles have a potential to become the next item in that row and observers of the smart textile innovation process forecast the technology to proliferate at the consumer market within a decade and become an integral part of future life styles in future.

Rich, unique, personalized material experiences [20,23] facilitated through smart textiles can result in an uptake of applications, such that smart textiles will gradually become more recognized and mainstream in daily used products [48]. However, these innovations and the high development speed involved have a counterpart as well: it raises concerns about environmental issues related to these trends.

A general observation is that smart textile designers, at least those working in small and medium sized enterprises (SMEs), are not well-educated and/or informed about issues related to design for sustainability [31]. There is a knowledge gap to bridge, not only to support the decisions and to fill up the lack of environmental knowledge of these designers, but of their managers and clients as well. Since textile designers make numerous product development choices and influence the architecture of products based on market and user insights [51], this study is specifically aimed at this audience group.

The contemporary innovation process of smart textile holds the opportunity to implement environmentally conscious design right

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from the beginning. This may help preventing adverse environmental side effects of tomorrow's products [26]. Our assumption is that textile designers can significantly reduce the environmental impact of their smart textile based products. This, we further assume, will require a design decision making process in which they are well-informed from an environmental impact and eco-design point of view — e.g. make the right material choices [22,34] — and on relevant user scenarios, at early design stages. In close connection, it is assumed that designers could communicate these well-considered choices successfully to their management, their colleagues at marketing and eventually to the consumer.

This paper provides a case study of a smart textile garment for health applications. It is introduced here to serve as an example on the potential of eco-design of smart textiles and to illustrate that these relatively complex products can benefit from life cycle thinking. The first part includes a LCA to determine the hot-spots of environmental impact associated with the product's life-cycle. The second part of the case study shows eco-redesigns, using the results of the LCA and the implementation of eco-design strategies. The authors aim for this first e-textile eco-design case to be a powerful example and illustration for smart textile designers, from which they can learn what aspects are important to take into account (and conversely, which can be safely ignored) when they want to put eco-design into practice in their fast emerging sector.

To test the eco-design approach we present in this article, we introduce the following hypothesis: The implementation of eco-design can improve the environmental impact of a smart textile product — expressed in eco-costs — with at least 25%.

The next sub-section (1.2) outlines the main environmental problems related to smart textile design while sub-section 1.3 reviews the status quo of LCA of e-textiles in literature. Section 2 explains the method of the study presented in this paper. Section 3 describes the case study of a specific smart textile product for the health application, called 'Vibe-ing'. Sub-sections 3.1 and 3.2 introduce the case-study and describe the prototype, while in 3.3 the LCA of Vibe-ing is being discussed. 3.4 then describes the application of several eco-design strategies on Vibe-ing based on analysis of redesign solutions. The paper ends with a discussion and conclusions in Section 4, including a discussion on the limitations of the research, the results pertaining to our hypothesis and recommendations for further research.

1.2. E-textiles and the environment

E-textiles are regarded as a subset of smart textiles, also referred to as 'wearable electronics'. These products differ from traditional fabrics in that analogue and digital electronic components — for example, small computers — are (more or less) seamlessly integrated into the knit, weave or other soft crafts technique [8,46]. The purpose of this integration is to obtain new functions of textile materials or, from the perspective of the electronic sector, to enable novel user experiences with electronic products that have not been soft and flexible thus far [25].

As the innovation system is yet at its pre-mature stage [7], a lot of functionalities are achieved by attaching or integrating the electronic components in- or onto the surface or to the textile product [29]. One step farther ahead in innovation and electronic functions is integrated right into fibres or yarns directly [32]. In essence, the fast-developing electronic sector bands together the change-minded fashion industry in an endeavour to create a new category of smart wearable products [44]. From an environmental impact point of view this reveals a lot of challenges [25] and hot spots comprise energy — and battery consumption; use of toxic materials and — of scarce resources and recycling difficulties. The same source highlights as well the attitude and expectations of smart-textile designers and — SMEs towards sustainability and LCA (*ibid.*). It indicates that the majority of SMEs do not see the environmental performance of products as a driver for innovations and environmental aspects are presently regarded to have inferior importance as compared to product functionality.

In terms of environmental concerns, it seems that there is still room for a prevention oriented approach: so far, smart textile technology has not produced a 'killer application', despite this already was discussed during the 7th edition of the Smart Fabrics conference in 2011 [42]. The 'kick-start of the smart clothing business' that has been announced with such conviction did not take place yet [6]. Not many smart textile products can be seen in the streets today and they are not yet integrated in the ready to wear clothing segment. While it is true that the integration of electronics in sports activities and sportswear is a growing trend, the consumer's need to self-monitor can also be addressed by means of separate accessories, e.g. a breast — and wrist device [37]. Likewise, smart textiles are indeed penetrating the healthcare — and the protective clothing markets [33,41], but again these are considered niche applications when compared to the worldwide apparel sector.

A possible explanation for the delayed market appearance of smart textiles might be due to technological limitations: E-textiles are yet not washable and the reliability is often poor. Then again, integrated electronics in textile cuddly toys (such as the once-ubiquitous 'Furby') and e.g. children's shoes (with flickering lights like 'Skechers') already are more and more present and this could indicate that the moment e-textile clothing products really break through might not be too far away.

From this observation it can be concluded that it is timely and opportune for the environmental problems surrounding e-textiles to be explored in depth so as to positively influence smart textiles innovation and development.

1.3. LCA and eco-design of e-textiles

LCA is a quantitative method to environmental assessment according to the international standards [16,17]. It is widely used to study the potential environmental impacts of processes, products and services through the whole life cycle from cradle to grave [14,39]. This encompasses the raw-material acquisition, the production processes leading to products, transport processes, the product's use phase and its end-of-life (EoL) stage. By means of the LCA-methodology, the environmental impact of a product can be assessed and compared with other products or alternative design solutions.

Eco-design comprises the integration of environmental aspects into technology development and product design. The overarching aim is reducing adverse environmental impacts throughout a product's lifecycle [10]. According to the EU Eco-design directive [12] a greater focus in eco-design is cast on the product's energy use and other environmental aspects during its complete life cycle. The Eco-design Directive emphasises the important role of the conception and design phases, before a product is manufactured and brought to market.

Both LCA and eco-design are extensively described in scientific literature, for example by Ehrenfeld already in the late 90s [11]; by Klöpffer [24] and Niinimäki and Hassi [36]; and recently by Mirabella et al. [35]. These and many other articles highlight the value of the implementation of LCA and eco-design for environmentally conscious product development.

The bibliographic database Scopus reports almost 500 articles with 'eco-design' in the title, abstract or keywords over the last five years (2010–2014), and almost 6400 with the term 'LCA'. Although a growing trend is visible, both subjects together in one article are less common (118 articles found). If the emerging technology 'smart textiles' or 'e-textiles' are concerned, only a few studies have been conducted thus far [25,27]. Schischke et al. [40] refer to the LCA-to-go project (see Section 1.1), which presents a simplified LCA approach for smart textiles. Similar results (0 papers found) came up when searching for combinations with the term 'wearable electronics'. The literature research highlights the fact that not many scientists work on eco-design of smart textile products and LCA-base knowledge is fairly scarce among technology developers and design practitioners.

A few environmental assessment studies on products with similar characteristics as smart textiles were identified, for example a LCA of a printed antenna [18] and a prospective environmental LCA of nanosilver T-shirts [56]. LCAs of textile products without smart functionality can be found (e.g. [30,52]). However, based on the above referenced studies — and because no LCA-studies of smart textile products could be found — it is not possible to formulate conclusions on behalf of the prospective LCA results of smart textile products, because the impact of the combination of textile and electronic materials in one product is not known.

2. Method

To test our hypothesis we performed a LCA of the Vibe-ing prototype (see Fig. 2). The LCA method is based on a system approach of the chain of production and consumption and analyses the input and output of the total system [17]. The LCA was conducted using the SimaPro (V.8) software and the environmental impacts are expressed in the indicator 'Eco-costs' according to the Eco-costs/Value Ratio (EVR) method as developed by Vogtländer et al. [54,53].

The Model of the Eco-costs is a convenient method to express the amount of the environmental burden of a product on the basis of prevention of that burden [55]. It provides for an easy comparison between design alternatives. The general rule for interpretation is: the lower the eco-costs, the better the alternative.

The calculation of the eco-costs is based on classification and characterisation tables (IPCC 2007, GWP 100 for global warming; ILCD for acidification; recipe midpoint for eutrophication; recipe photochemical oxidant formation for summer smog; RiskPol for respiratory inorganics and Usetox for ecotoxicity and human toxicity, cancer). However, it has a different approach (see Fig. 1) to the normalisation and weighting steps than the classical way to calculate a 'single indicator' in LCA. Normalisation is done by calculating the marginal prevention costs for a region (i.e. the European Union) to determine the eco-costs of emissions. The weighting step is not required in the eco-costs system, since the total result is the sum of the eco-costs of all midpoints [13].

Next the results of this LCA were used to determine which eco-design strategies were selected for the eco-redesign options. In the eco-design process we used the Life Cycle Design Strategies (LiDS) method developed by Brezet [3] and described in sub-section 3.4.1.

Finally the environmental gains of each strategy were calculated and tested against the hypothesis.

3. Case-study of Vibe-ing

3.1. Introduction

The Vibe-ing product concept (see Fig. 2) was chosen for the case-study, because in this specific smart textile health product, the textile and electronic materials are very closely interwoven. Other smart textile products, for example 'Textales' [47], do not include the same integration of textiles and technology, which was the most important selection criterion for the case study.

The knit of Vibe-ing has specially designed pockets (see Fig. 4) for the electronics to fit in, and the microchips with the 3D printed cases are specifically constructed for the knitted pockets on the garment. In addition, the Vibe-ing is still on a prototype level, which means that the results of the eco-design process can be implemented in an early stage of development, before entering the market.

3.2. The prototype

This section describes the prototype and the material choices in the design process and also the envisioned service system and the use — and end of life phase of the product. These aspects are looked into in detail to be able to assess the full life cycle of the Vibe-ing and for the reader to understand the background and the usage of the product.

Vibe-ing a self-care health product in the form of a garment, which invites the body to feel, move, and heal through the vibration therapy. It has been developed collaboratively within the Dutch Creative Industry Scientific Programme [5] Smart Textile Services project by partners from Eindhoven University of Technology (Eunjeong Jeon, Kristi Kuusk, Martijn ten Bhömer), Metatronics and the Textile Museum TextielLab Tilburg. Vibe-ing has been develop to explore the possibilities for integrating textiles and technology. It is a further developed prototype from 'Tender', which is a knit garment with lights, that turn on and off depending on the movement of the wearer, integrated into the garment's pockets. One of the conceptual directions explored for the use of such integration was vibration therapy. The suggestion is purely inspirational and is set up for the health care professionals to pick it up for actual and further validation and development. The use of Vibe-ing in the case of the treatment of osteoporosis is discussed in [49]. Vibe-ing has to be worn next to the skin, because the knitted textile sensor reacts to the capacitive touch, therefore only by the contact

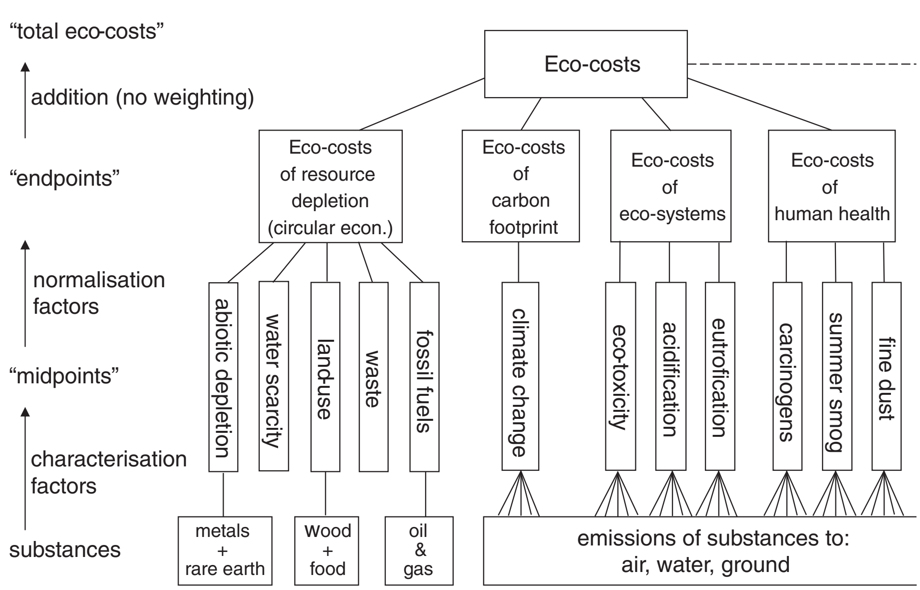

Fig. 1. The structure of the system of the eco-costs.

Fig. 2. Photo of Vibe-ing, by Wetzer & Berends.

with the body. An undergarment can be worn as long as it does not create a layer between the body and Vibe-ing.

Vibe-ing is knitted in the Textile Museum TextielLab in Tilburg, using the STOLL 430 TC fully fashioned knitting machine. It consists of several types of knit areas as depicted in Fig. 3.

Each of them, according to the need of the specific function, has a certain amount of in-knit pockets (see Fig. 4) situated in a specific way (see Fig. 3). In the pockets are 3D printed casings (see Fig. 7, 1.2.2.1 Casing shells) with one flat side and one structured side, to invite moving direction and stimulate the touched area more intensively. The casings accommodate motor chips (see Fig. 7, 1.2.1.1 CRISP motor Printed Circuit Board) and vibration actuators, which can have different programmes on them depending on the specific person's need for rehabilitation and vibration stimulation. For instance they can react to the touch of the person (or therapist) simultaneously or they can vibrate according to a specific programme fine tuned for the specific user. This allows the garment to behave differently by the means of digital changes. The Vibe-ing is designed with the intention to be worn in four different manners (see Fig. 5a–d). This changeable way of wearing Vibe-ing, allows more body areas to be stimulated by the vibration elements with the use of minimal electronic components possible.

Vibe-ing is mainly knitted of Greggio Millennium yarn — for the specific soft feel and wool properties it has — with some lines of metallic silver coated yarns, which were chosen for its functionality as well as for styling reasons [49]. The aim was to create an aesthetically pleasant

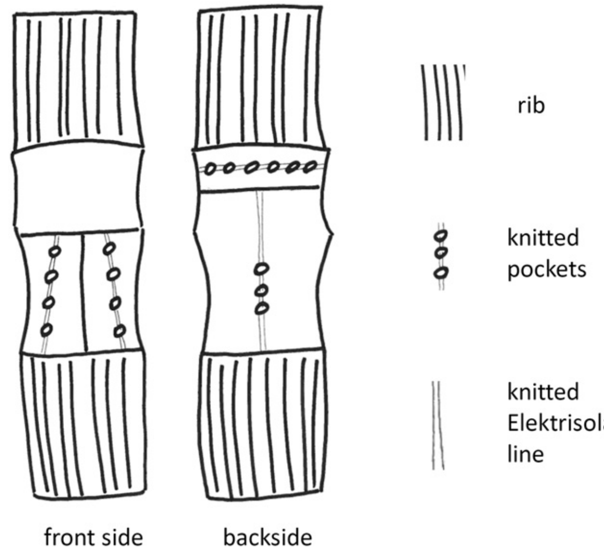

Fig. 3. Illustrative technical drawing of the complete Vibe-ing.

structure where the metallic yarns could be part of the design and stand out as contrasting cold elements inside the otherwise warm wool structure. Steaming the merino wool creates the combination of flat and bulky areas on the textile surface for a pleasant touch.

As estimated by the designers, on average the Vibe-ing garment would be used for five years. Within those years there would be five cycles of one year's use cases. In the beginning, the wearer would receive the Vibe-ing garment from the medical contact person. Together they personalise the behaviour of the vibration pattern according to the wearer's needs. After one year the wearer would return the Vibe-ing to the care organisation where the staff makes sure it is cleaned, sent to maintenance if needed and re-customised for the next patient. During this annual maintenance Vibe-ing would be checked and textile parts together with electronics and the connections fixed if needed. Over the regular use period Vibe-ing would be used by one person at a time and be active 2–5 times per week for 10–30 min per time. During this period, adjustments and updates of the electronics would occur digitally and on distance. The maintenance would be done by the means of cold wash and air-dry at home. After this life the Vibe-ing would be used up and discarded. Note that the suggested time usage and frequencies are based on fictional use case scenarios and should be further validated once the second generation of Vibe-ing will be developed.

Fig. 4. Knitted pockets.

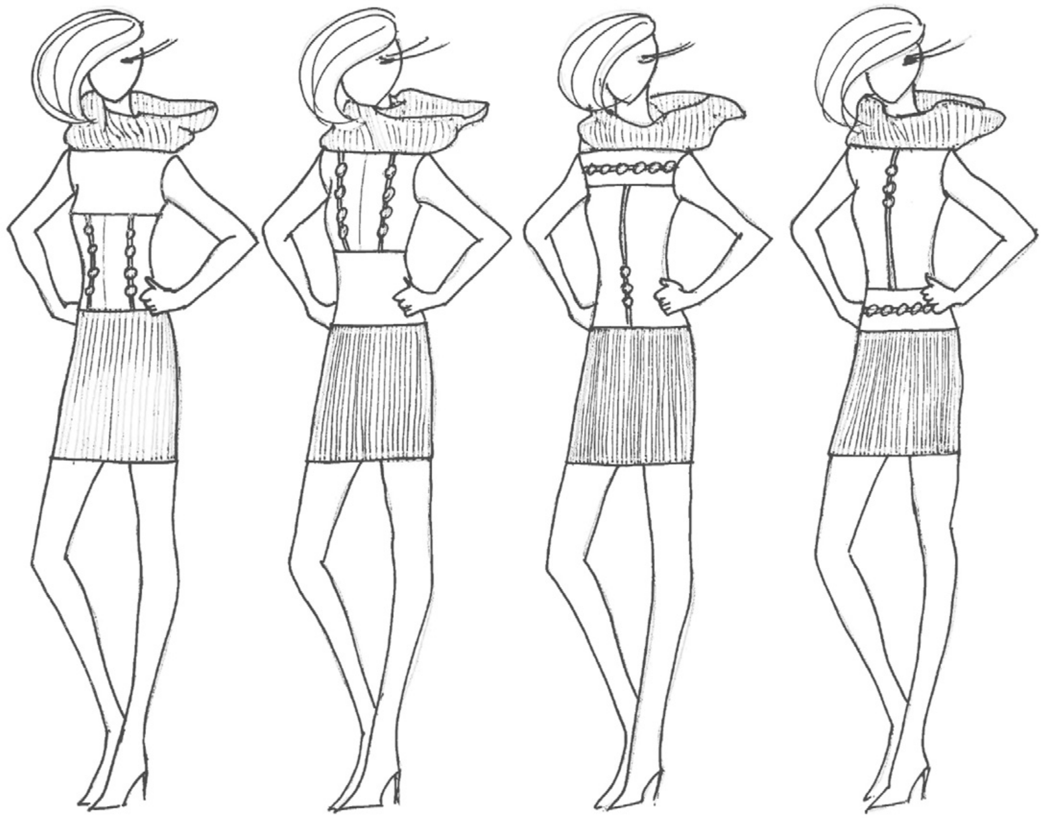

Fig. 5. a–d. Illustrative drawings of Vibe-ing, showing the four ways it can be worn by the wearer, to stimulate different areas of the body.

3.3. Life cycle assessment of Vibe-ing

3.3.1. Goal and scope

This LCA was performed to find out areas for eco-redesign of the prototype of the smart textile product Vibe-ing.

The scope for the LCA is cradle to grave and covers all life cycle phases of the product, including the manufacturing, use, transport and disposal lifecycle phases as described above in Section 3.2. The packaging of the product has been excluded of the boundary assessment.

The functional unit is: Five times the treatment of a Dutch woman — who is in need for vibration therapy — by means of Vibe-ing, for a use period of one year; 5 times per week; 30 min per time.

3.3.2. Inventory analysis

The processes accompanying the lifecycle of the Vibe-ing are shown in Fig. 6. The product exists of a textile body (numbered 1.1 in Fig. 6) and an electronic system (number 1.2), which are manufactured by the previous processes as shown in this chart.

The product parts described in the second column of Fig. 6 are depicted in the photos below (Fig. 7) to make clear what these parts look like.

For all stages named in Fig. 6 data about the material composition, manufacturing methods and transport were collected, as well as data on the subsequent processes. These life cycle inventory (LCI) data were derived from mixed sources including: Ecoinvent V3.01 [9]; Idemat 2014 [15]; lab tests; machine manufacturers and literature [2,38,45].

Transport takes place between the different manufacturing locations of the production areas overseas (the boxes with the red outline in Fig. 6). The merino wool is produced in New Zealand and processed in China resulting in yarn that is shipped to Europe. The Lycra originates from Germany and the electronic components are sourced from China. In-house production (all processes in the boxes with the green outlines) takes place at specific workplaces in Eindhoven and Tilburg, the Netherlands.

For this LCA it is assumed that both — the medical care operator and the ‘patient(s)’ are located in Eindhoven (within 10 km distance) — where the prototype of the Vibe-ing is designed and made as well. According to our scenario, the patient visits the medical practitioner by car at the begin, several times during, and at the end of the therapy phase. At this occasion, the Vibe-ing is handed over to the patient and returned to the practitioner after usage. When obsolete, the Vibe-ing is discarded and disposed of in the Netherlands where state-of-the-art municipal waste treatment facilities are in operation.

The product system under study includes all processes related to the complete process tree of Vibe-ing as depicted in Fig. 6. The system boundary can be drawn as a circle around the complete diagram. The Bill of Materials (BoM) and Eco-invent V3.01/Idemat V2014 background processes are provided in Table 1 in Annex A.

3.3.3. Impact assessment results

Fig. 8a–d presents an overview of the LCA impact assessment results over the Vibe-ing lifecycle. Noteworthy that transport during use and transport during end of life (EOL) appear to have a significant impact in these specific phases. Fig. 7b and c are presented to show this effect.

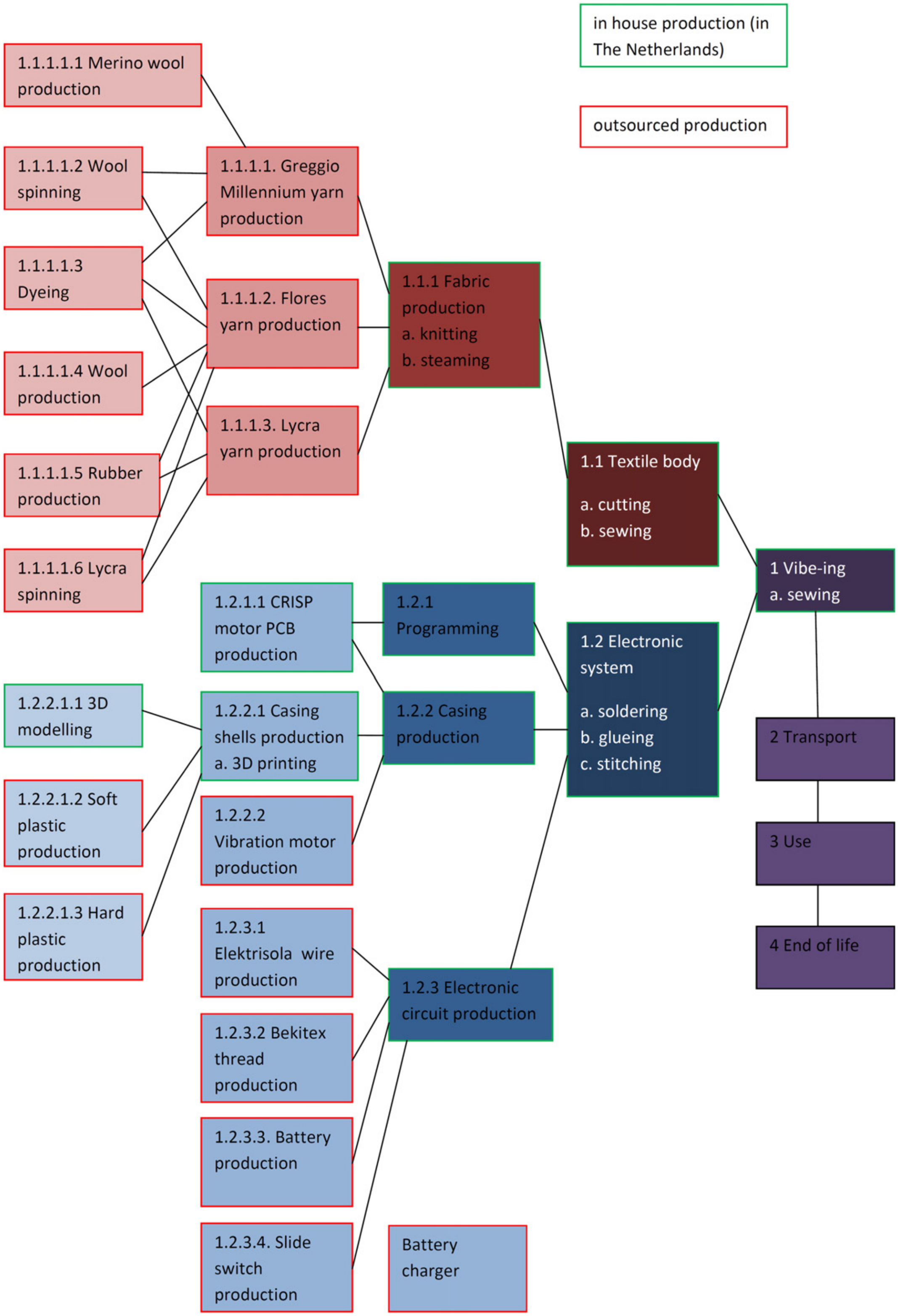

Fig. 6. Process tree diagram of Vibe-ing.

Fig. 8d presents the eco-costs of the Vibe-ing production phase and shows the breakdown over the textile body, the electronic system and the battery charger.

Fig. 9a–d presents the detailed environmental impact of the Vibe-ing production phase. Fig. 9a shows the eco-costs for the electronic system and Fig. 9b the division over the Electronic circuit of which the impact is completely caused by the production of the Elektrisola yarn. Fig. 9c presents the breakdown over the textile body and Fig. 9d the division over the production phase of the material with the biggest impact, namely the Greggio Millennium yarn production.

It is noteworthy that certain processes from the process tree in Fig. 6 do not appear in the graphs of Figs. 8 and 9 because we applied the cut-off criterion of 1% (in compliance with [17] Section 4.2.3.3) to decide on the exclusion of (sub)processes, inputs and outputs.

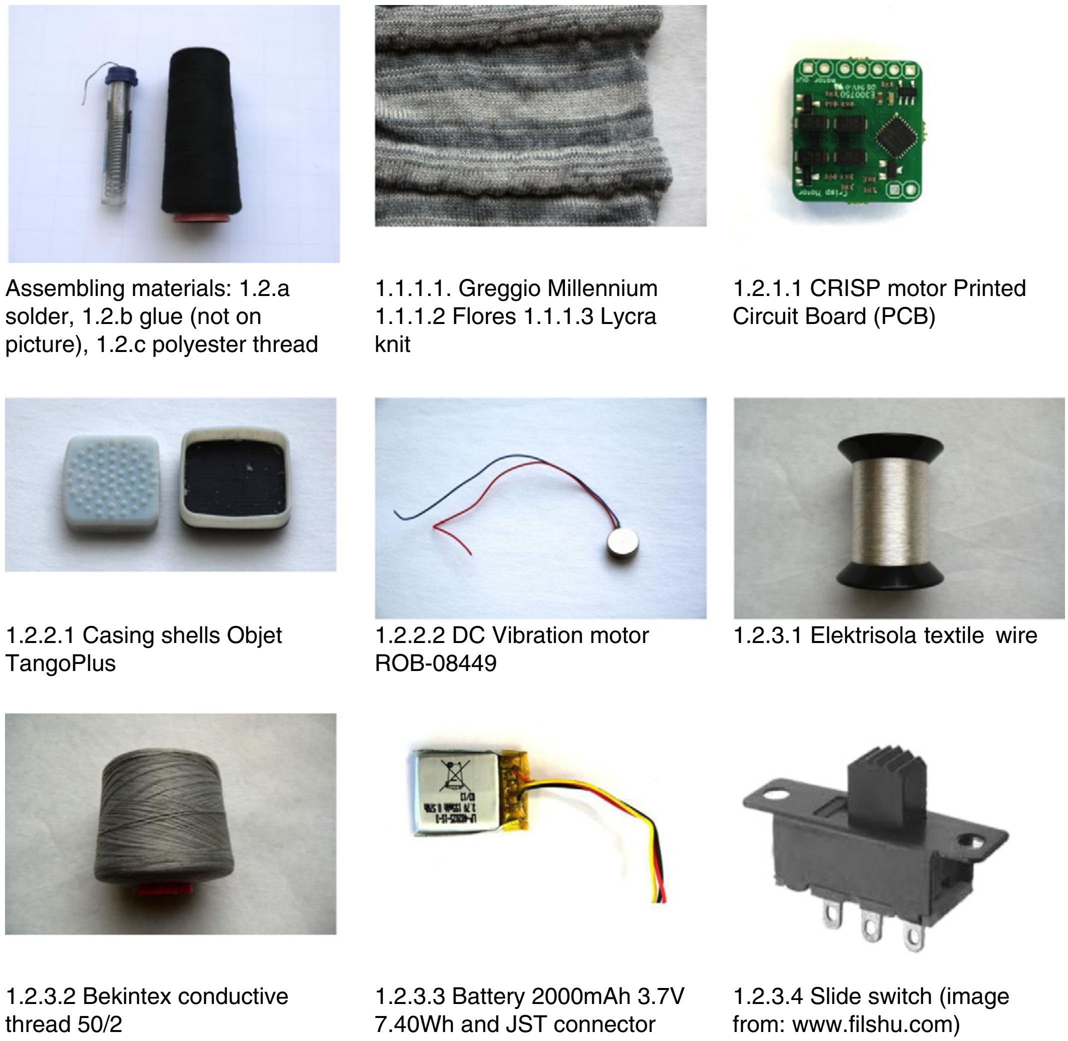

Fig. 7. Photos of the textile and electronic materials used in Vibe-ing.

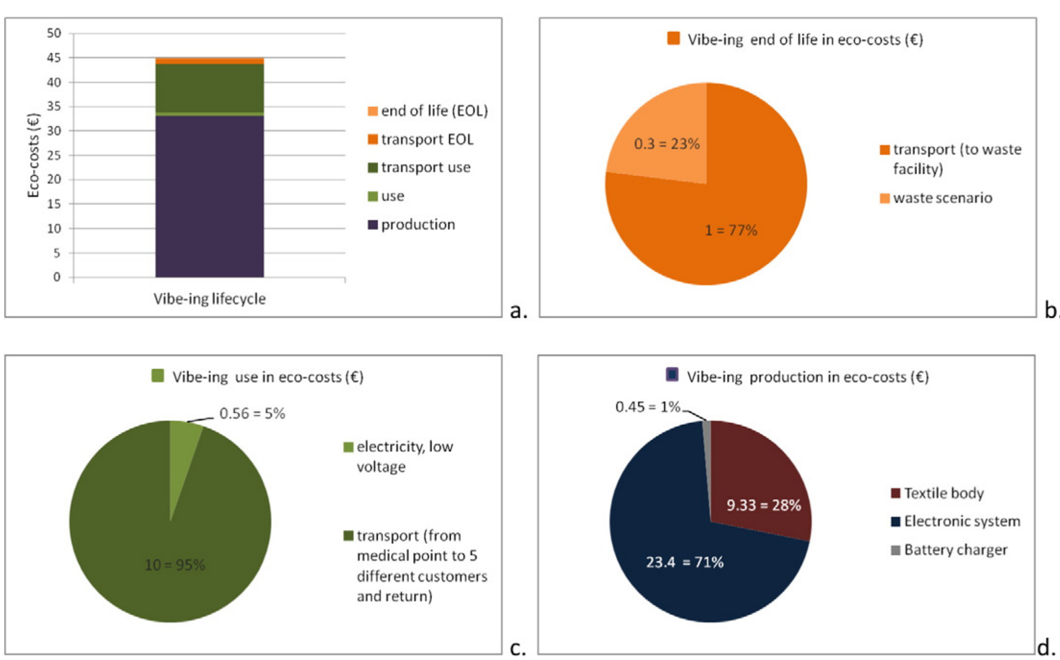

Fig. 8. a–d. LCA results over the Vibe-ing life-cycle per life cycle phase.

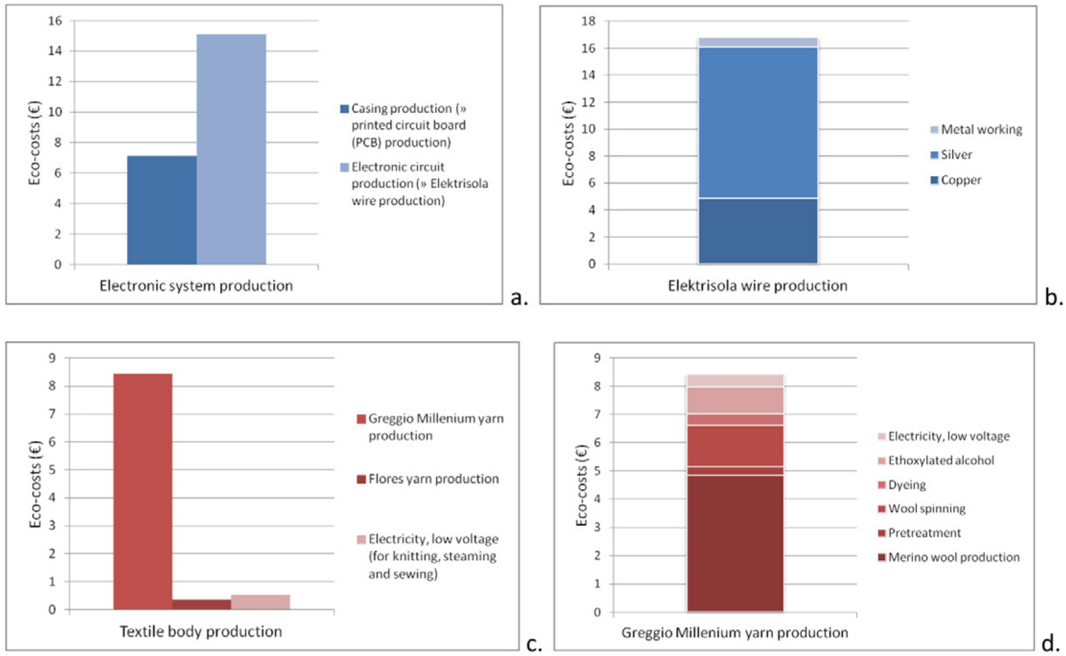

Fig. 9. a–d. Environmental impact of the Vibe-ing production phase.

Calculations for the environmental impact in three other frequently used indicators — namely: CO_2 equivalent (CO_2 eq.), Cumulative Energy Demand (CED) and ReCiPe (H/A weighting) — were made as well. However, these did not yield satisfactory results because not all of these indicators include all impact categories — such as human toxicity, eco-toxicity, materials depletion and land use. These data are available though and can be provided upon request.

3.3.4. Interpretation

Over the life-cycle of Vibe-ing, the production phase — with eco-costs of €33.2 — has the biggest environmental impact, followed by the use-phase (€10.6) and the EOL (€1.3), see Fig. 8a.

The domestic transport during use has a relatively high impact and accounts for 95% of the impact of this phase (see Fig. 8c) due to the numerous drives by personal car between the medical point and the different patients which will use the Vibe-ing during the lifespan. In the EOL the transport phase has a much smaller impact of 23%, see Fig. 8b.

Interestingly the outcome related to the impact of 'transports' during the production phase of Vibe-ing is in contrast with the general idea about the impact of this life cycle phase. The common thought is that the travelling of materials 'around the world' (e.g. in this case the wool from New Zealand and electronic parts from China) has a huge impact. The LCA outcomes do not confirm this and show that the transport during the use phase and during the EOL phase (which is the physical transportation of the complete Vibe-ing product from and to the customers and the waste processing facility) has a much bigger influence than the transport of the feedstock materials during the production phase — which stay below the 1% cut-off limit — (see Fig. 9a–d and text under this Figure). Throughout the use-phase of Vibe-ing the eco-costs of the electricity use are comparatively low, which is due to the relatively low-power utilisation of the battery powered electronic components integrated in the textile.

During the Vibe-ing production phase the biggest impact (71%) comes from the electronic system, followed by the impact of the textile body (28%) and the battery charger (1%).

The impact of the electronic system (€22.2, see Fig. 9a) is for 68% determined by the Electronic circuit production — which in itself completely comes from the production of the Elektrisola wire. Fig. 9b shows that the high silver content is responsible for 2/3 of the impact of this wire.

Furthermore it can be concluded that the 3D printed casing shells have a negligible impact. The eco-costs of the casing production are determined by the PCB production only, see Fig. 9a, and contribute for 32% to the eco-costs to the electronic system.

Finally the impact of the textile body production is mainly due to the production of the Greggio Millennium yarn (see Fig. 9c). Fig. 9d shows that the Merino wool production causes a considerable part (57%) of the impact of this yarn.

3.4. Eco-design of Vibe-ing

3.4.1. Selection of eco-design strategies

To practise eco-design — with the goal to lower the environmental impact of the alternative product design option — several eco-design strategies are recommended in literature. These strategies are depicted in the Eco-design Strategy Wheel [4] in Fig. 10, which shows an example of the application of this Wheel in case of a random product. The — in this figure randomly chosen — points on the axes represent the degree to which a certain strategy is taken into account: The closer to the outside of the circle, the better. The diagram shows that the eco-redesigned product (dark grey) scores better on all strategies than the original design (light grey). This can be concluded by comparing the respective points on the axes and by the fact that the surface of the dark grey figure is larger than the light grey one. Furthermore Strategies 1 and 8 stand out; Strategies 4 and 5 show the least improvement. Note that this Fig. 10 only demonstrates the Wheel to serve as an illustrative example for 'any product' and that Fig. 11 presents the Eco-design Strategy Wheel for the specific case of Vibe-ing.

For the eco-redesign of Vibe-ing the LCA-results are used to inform and guide the eco-design strategies to be selected. From the Figs. 8 and 9 and the LCA interpretation it can be concluded that Strategy 1 Choice of materials and Strategy 2 Material reduction are the most promising approaches to reduce the overall environmental impact of Vibe-ing, because the materials (Merino wool and Electrisola yarn) significantly contribute to the environmental impact of Vibe-ing.

3.4.2. Eco-redesign options

In this section the eco-redesigns of the Vibe-ing are described with reference to the selected eco-design strategy. Additionally, during the eco-redesign process, we identified some other relevant approaches.

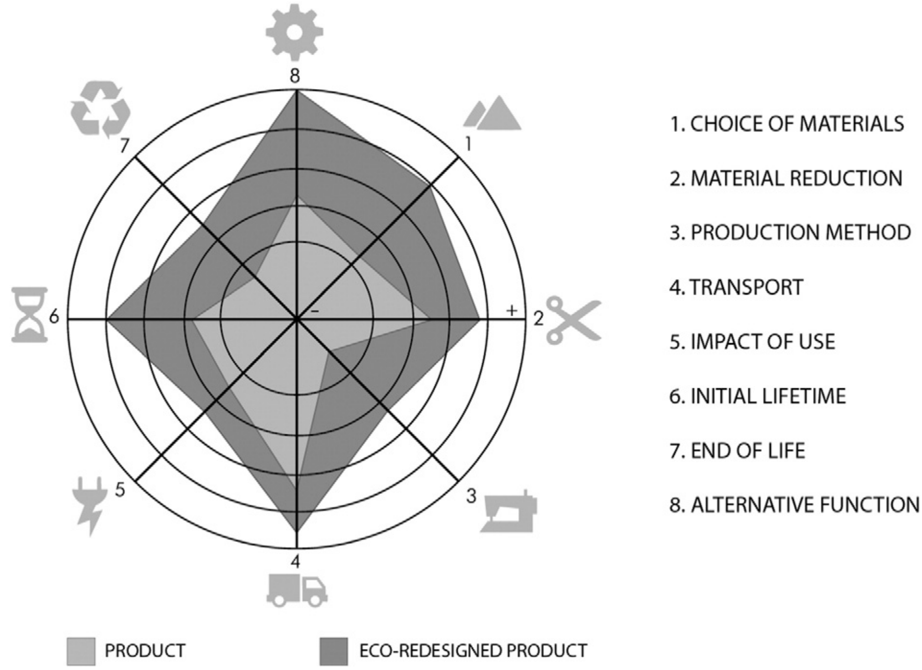

Fig. 10. The Eco-design Strategy Wheel, graphical reproduction designed by K.M. Lussenburg.

These extra options are described in the second part of this paragraph (starting with Eco-design strategy 3). An overview is given in Table 2 and Fig. 11.

The numbers in the naming of the redesigns of the Vibe-ing correspond with the numbers of the strategies (e.g. for Eco-design 1a the Strategy 1 Choice of materials has been applied).

For Eco-design 1a, the Greggio Millennium wool (= the Merino wool) is substituted by acryl, which reduces the impact of the textile body by 73% (because the eco-costs for producing acryl are 80% of the eco-costs of producing merino wool). Consequently the eco-costs of the complete Vibe-ing (textile body + electronic system) decrease by 22% to a total of €25.96.

Currently, the only available alternative to wool, showing approximately similar functional performance is the full synthetic textile material 'acryl'. The disadvantage of acryl is that in its current applied state it does not have the natural properties that wool has, such as a self cleaning; anti-bacterial; anti-odour and breathable function. The choice for acryl might have consequences for the use-phase because the user of the acryl product might sweat more and the textile might capture more body-odour. As a consequence, applying this Eco-design 1a-inspired design solution is likely to result in more intensive cleaning. This so called 'secondary effect' can be described as the counter effect of a certain environmental improvement. In this case the extra laundering treatment is not expected to significantly influence the (new) eco-costs because

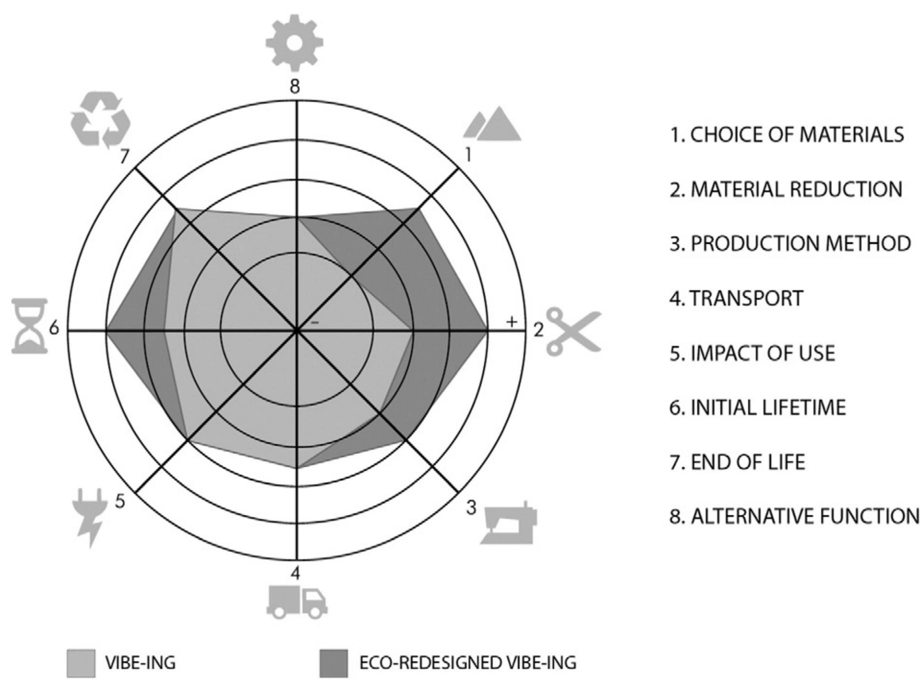

Fig. 11. Eco-design Strategy Wheel with the Vibe-ing and the eco-redesigned Vibe-ing.

Table 2
Overview of the eco-designs, -strategies and -measures and their consequences.

	Eco-design strategy	Improvement measure	Eco-costs savings	Design implications	Secondary effect
Eco-design 1a	1 Choice of materials	Replace wool by acryl	Textile body 73%; Vibe-ing redesign 22%	Different look, feel and touch (for experts)	More intensive laundering
Eco-design 1b	1 Choice of materials	Replace Elektrisola by copper wire	Electr. system 45%; Vibe-ing redesign 33%	Different look	None
Eco-design 2a	2 Material reduction	Minimise usage Elektrisola with 75%	Electr. system 51%; Vibe-ing redesign 36%	Communication modules; different look	None
Eco-design 2b	2 Material reduction	Omit collar and skirt	Textile body 60%; Vibe-ing redesign 18%	Wearing comfort; design	Extra clothing or ambient heating
Eco-design 3	3 Production method	Other knitting technique	Textile body 45%: Vibe-ing redesign 14%	Different feel and look; wearing comfort	None
Eco-design 6	6 Initial lifetime	Extend lifetime with 50%	Vibe-ing redesign 33%	None	None

Electr. = electronic.

the laundering must still be done with cold water and by hand (warm water and laundering machinery will destroy the knit and the functioning of the electronic system) with minimal use of detergents.

Eco-design 1b reduces the high impact of the silver content in Elektrisola by substituting this material with an alternative that mainly consists of copper. Copper accounts for about 1.4% of the eco-costs of silver while having similar functional properties (conductivity). This measure decreases the eco-costs of the electronic system by 45% and those of the Vibe-ing redesign by approximately 33%. A copper wire has a different look than the silver-coloured base-material so this measure will affect the look of the design.

For Eco-design 2a a material reduction of 75% of the amount of Elektrisola is proposed. According to the designers it is expected that this measure will not affect the separate operation of the vibration elements, but it might have an effect on the communication between the modules. Whether this aspect is important for the operation of the Vibe-ing and the healing therapy must be further explored by means of field-testing and cannot intuitively be addressed. However this strategy will reduce the eco-costs of the electronic system by more than 50% and those of the Vibe-ing redesign with 36%.

Regarding this measure it is important to mention that the Vibe-ing designers deliberately chose to apply this amount of Elektrisola for aesthetic reasons (the silver colour) and because they wanted to knit the product fully fashioned — as automated as possible — and minimise the handwork. Referring to the latter it would be an option to look for another automated way to knit-in less wire or maybe alter the design so automated wiring would still be possible with less material.

Eco-design 2b applies material reduction by leaving out the skirt and the collar of the original design, which saves approximately 2/3 of the textile use and respectively 60% in eco-costs of the textile body. For the working of the electronic system this measure does not make any difference, but only the appearance and the wearing comfort of the design will be different. While body warmth might positively influence the healing process the therapist might recommend an extra warming element or to heat up the ambience where the patient uses the Vibe-ing. The latter might be an unwished secondary consequence. To come across this effect and simultaneously lower the impact of the product (system), the designers could decide to produce the collar and the skirt apart from Vibe-ing (as separate items) so these could be worn in combination with the Vibe-ing top and occasionally with other tops as well.

Eco-design strategy 3 is about the production methods. In first instance it was expected that the 3D printing of the casings would have a substantial influence, but the LCA base-case calculations do not confirm this. Although the knitting process itself does not have a large influence (the impact of the electricity use of this process is minor, see Fig. 8c.), the choice of the designers to apply the specific jacquard knitting technique has significant consequences for the amount of material to be used. Jacquard knitting creates a voluminous and comfortable structure, but consumes additional material (and energy) because — in simple words — the knitting movement is executed twice. By choosing another — more simple — knitting method it is estimated that 50% of the knitting material can be saved which gives a reduction of more than (because for this rule of thumb calculation the energy savings and the material savings of the electronic materials are not taken into account) 45% of the impact of the textile body and more than 14% of the assembly. Since for this redesign the surface of the dress remains similar to the original, the secondary effect because of extra ambient heating (as for redesign 2b) is expected not to take place. The difference with the Vibe-ing prototype will mainly be that the body-material will be thinner, which will have an effect on the feeling of wearing but it is expected that the thinner material will be enough to give the body the necessary warmth for the treatment.

In case of other energy-using products for which the use-phase has a high impact due to electricity use, extending the lifetime (Eco-design strategy 6) might not make sense, because the benefit of more energy efficient technologies could mean that it would be a better to replace the product by a new one. For example in case of a washing machine, the calculation of the optimum lifespan should bear in mind the balance between the environmental cost of producing this machine and the environmental cost of using it [1]. For Vibe-ing the impact of electricity use during the use-phase is of minor importance and the production phase has a high impact. Application of Eco-design strategy 6, for example by a lifetime extension by 50% would approximately reduce the environmental impact by at least 33% ($= 1 - 1/1.5$; benefit of technological update not included).

Fig. 11 graphically presents the effects of the application of all eco-design strategies discussed in this section in the Eco-design Strategy Wheel in a qualitative way. The light grey surface reflects the Vibe-ing prototype and the dark grey surface — which is partly covered by the light grey one — represents the Vibe-ing eco-redesign. The outer points of the figures (surfaces) indicate the degree to which a certain eco-design strategy was taken into account.

For instance in Fig. 11 the point on Axe 1 (representing Strategy 1. Choice of materials) of the light grey surface only touches the first inner circle, which means this eco-design strategy was not taken into consideration while designing the Vibe-ing prototype. The designers principally chose the materials because of aesthetics; functionality and comfort, and not because of the related environmental impact. The outer point of the dark grey surface on Axe 1 is placed further to the outside of the Wheel because the choice for alternative materials (acryl and copper instead of wool and silver) positively affects the environmental profile. In the same way all other Strategies are mapped out in the Wheel in Fig. 11 to picture a qualitative overview of the eco-design strategies which are taken into account for the eco-redesign of Vibe-ing.

4. Discussion and conclusions

From the market perspective smart textiles have not yet spread into everyday casual wear. Since e-textiles are set to proliferate the worldwide 'fast fashion' apparel sector in future, all environmental aspects related to the complete life cycle must be taken into account already in the design stage. For now we can already discuss the prospective environmental problems around e-textiles in an early stage of innovation. In this discussion, the possibility that the development of smart textiles — whether or not in combination with service systems — could lead to sustainable products and — product service systems (PSS), should be included [28].

This paper only presents one iteration of the eco-design process. A complete process would include a second LCA of the redesign. The authors realize that the foundations of the arguments by means of the assessment of one case-study are only explorative by nature but we hope this study will be the incentive for more research, particularly on LCAs and eco-design, publications and a broader debate on the sustainability of smart textiles.

In the study presented in this paper we showed that, over the lifecycle of the smart textile garment for the health application, named 'Vibe-ing', the production phase has the biggest environmental impact (74% of the total), in which the electronic system accounts for a significant contribution (of 71%), mainly due to the silver content of the conductive wire. For the textile body the merino wool determines an important part of the impact (57%). During the use-phase of Vibe-ing the eco-costs of the electricity use are relatively low (5%) whereas the impact of domestic transport during this phase is very high (95%).

In the introduction of this paper, we had emphasized the rising interest in applications made of smart textiles or materials due to their high potential to create unique, rick and personalized material experiences. Thus the main purpose of the material in many applications is to evoke such user experiences. When the focus is on 'environmental aspects', however, we argue that many required 'smart effects' could be achieved through alternative materials with less environmental impacts. Designers who design with smart materials should consider such alternative solutions, through which they will not compromise the targeted user experiences. Studies concerning 'how materials are experienced and how they can be used interchangeably to create unique user experiences' [19,21] will help designers to assure that the materials they use as environmentally sensitive alternatives will elicit the user experiences they aim for.

In case of the Vibe-ing prototype the most beneficial eco-design strategies are 1. Choice of materials, 2. Material reduction, and 6. Initial lifetime. Three out of six eco-redesign options of Vibe-ing support our hypothesis, which states: The implementation of eco-design can improve the environmental impact of a smart textile product — expressed in eco-costs — with at least 25%. In this case-study our hypothesis is confirmed.

This research found that conscious material selection — in this case the decision to apply acryl instead of merino wool and to make use of copper conductive wire instead of wire with a high silver content — significantly reduces the environmental impact of smart textile products.

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