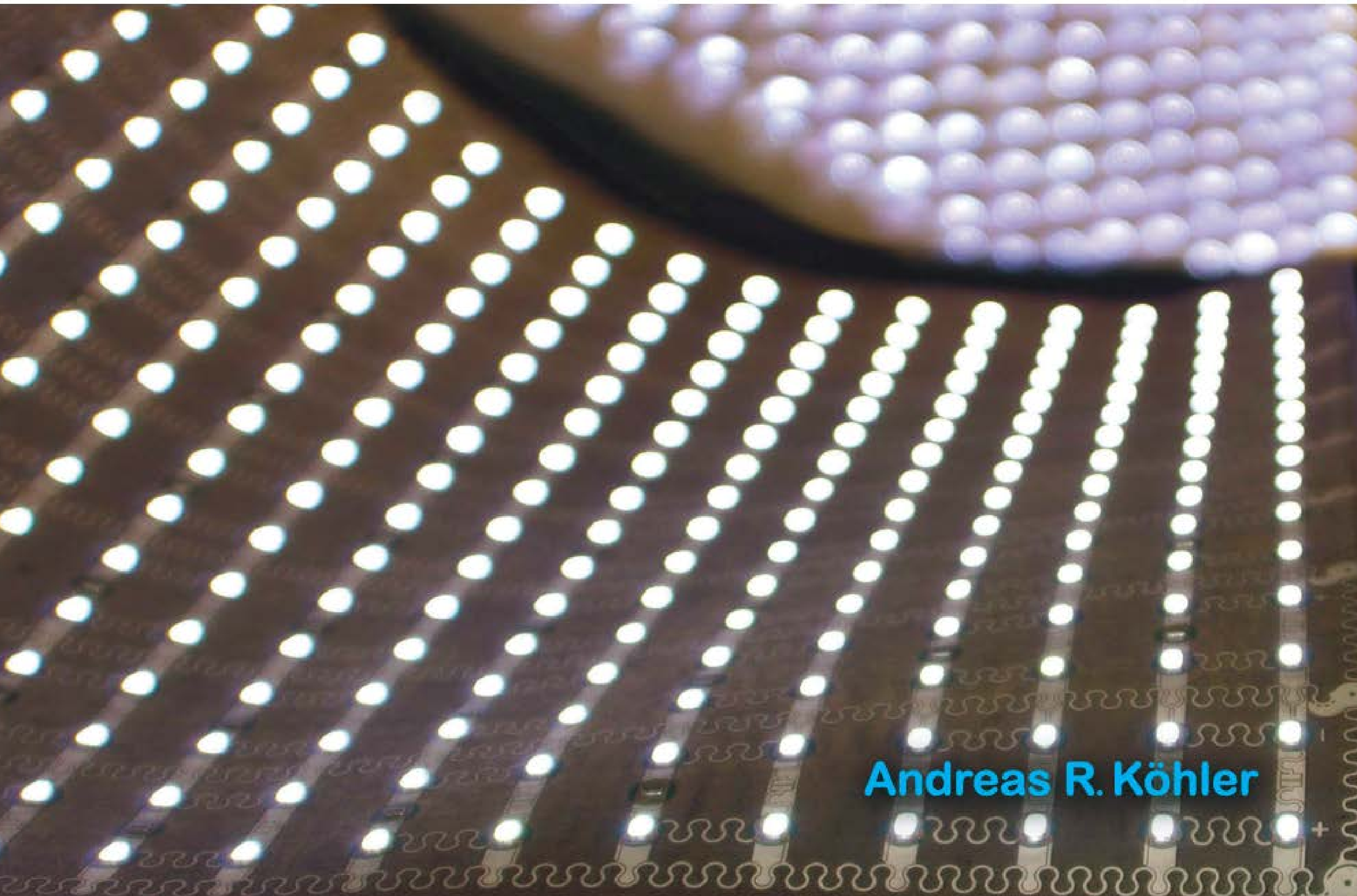
Anticipatory Eco-Design Strategies for Smart Textiles

Perspectives on environmental risk prevention in the development of an emerging technology



Andreas R. Köhler

Anticipatory Eco-Design Strategies for Smart Textiles

Perspectives on environmental risk prevention in the development of an emerging technology

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Table of Contents

SUMMARY

High-tech product innovations have led to adverse side effects with respect to environmental sustainability. The early stage of innovation provides good opportunities to counteract environmental risks before they materialise. This dissertation explores anticipatory eco-design strategies that could help in mitigating prospective environmental risks of smart textiles. Smart textiles are studied as an example of emerging smart technologies that may become a part of everyday life in the near future. The main research question of this dissertation is:

"How can environmental risks of emerging technologies be prevented at an early stage of the innovation process?"

The dissertation encompasses a compilation of published and submitted research papers, which are preceded by an introductory chapter 1 explaining the analytical framework as well as the research objectives and the research questions. The papers address different risk aspects related to smart textiles and discuss risk prevention strategies from the perspectives of sustainable innovation and eco-design.

Chapter 2 examines the anticipated environmental impacts of pervasive computing. This emerging technology is portrayed as a mega-trend of innovations in the ICT sector, and smart textiles are considered to be a subset thereof. Two major environmental risks have been identified: increasing consumption of scarce raw materials combined with increasing amounts of difficult-to-recycle electronic waste. Moreover, energy consumption will increase as myriads of tiny electronic devices pervade the market. Smart products, for example intelligent household goods, can also help in optimising the energy and material efficiency of other production and consumption processes. The extent of positive and negative effects depends on how effectively sustainable innovation policies govern the development of ICT infrastructures and products in the coming years.

Chapter 3 takes a closer look at the prospective end-of-life implications of one particular family of pervasive computing devices: electronic textiles. These novel high-tech products consist of small electronic devices, which are seamlessly embedded into clothing and technical textiles. The examination of their possible end-of-life implications suggests that such products may, if they become mass consumer applications, result in a new kind of waste that is difficult to recycle. The magnitude of future e-textile waste streams has been estimated, based on scenario calculations that draw from experiences with the previous market penetration rates of mobile phones. Large amounts of waste can be expected to be generated, if e-textiles become commercially successful products. The article concludes that the innovation process of e-textiles could hold opportunities to prevent future end-of-life impacts.

Chapter 4 elaborates further on the concept of risk prevention at the early stage of technology development. At first, the case studies on smart textiles and nano textiles are picked up and the environmental, health, safety and sustainability (EHS/S) risks of these technologies are outlined. Poorly managed EHS/S risks can entail enterprise risks for companies that develop their business plans around emerging technologies. By putting the discussion of EHS/S risks

into the context of business risk management, it is shown that enterprises have the potential to implement risk preventative innovation strategies for emerging technologies. Companies can hedge against adverse business impacts of EHS/S risks by implementing life cycle thinking and eco-design in the product development process.

Chapter 5 elaborates in more detail on the eco-design challenges of e-textiles. The conclusions of the previous two chapters are taken as a starting point for more viable design strategies that counteract future waste problems with electronic textiles. Design experiments with e-textiles serve as a test-bed to adopt Design for Recycling principles. It is shown that the existing eco-design concepts are in need of revision, as they do not match with the properties of the converging technology. The chapter maps out possible eco-design strategies for the end-of-life phase of e-textiles. It is argued that technology developers ought to develop and adopt compatibility standards in order to avoid progressive obsolescence of future e-textiles. In addition, smart materials and smart labelling offer new opportunities to facilitate the recycling of these high-tech products.

Chapter 6 looks into the applicability of Life Cycle Assessment (LCA) as a decision support instrument for the environmentally conscious development of smart textiles. A survey of Small and Medium sized Enterprises (SMEs) in the smart textile sector is provided. The results show that these companies hardly use LCA during the product innovation stage. A LCA about one example of a smart textile product demonstrates that even a preliminary LCA can set eco-design activities in motion during the development of smart textiles. The chapter then outlines a methodological concept of an LCA-based design decision support tool for SMEs in the smart textiles sector.

Chapter 7 takes a different perspective on risk prevention at the early stage of innovations. The criticality of raw materials is examined as an example of an intangible risk that is difficult to appraise due to the complexity and uncertainty of influencing aspects. The chapter explores why industrial designers and engineers should care about unintended implications of technological progress. Chapter 8 elaborates further on the reasons to increase the awareness of industrial designers and engineers about the limits in availability of critical materials. It is argued that materials criticality can give a fresh impetus to the education of industrial design engineers. It is important to train future professionals to apply a systems perspective to the process of technology innovation, enabling them to thrive under circumstances of constrained material choices. The conclusions outline ideas on how to weave the topic into existing educational programmes.

Chapter 9 summarises the answers to the research questions raised in this dissertation and draws conclusions. The dissertation elaborates anticipatory strategies the prevention of environmental risks concurrent to the innovation process of smart textiles. These strategies encompass: The use of eco-design heuristics based on life cycle assessment. Developing the education and skills of industrial designers and engineers to enable them working out and implement concrete eco-design measures. And, raising the risk awareness of industrial designers and engineers and forming attitudes to counteract risks proactively.

CHAPTER 1

Introduction

1.1. Preamble

Globally, the production and consumption of goods and services (products) are major sources of anthropogenic environmental impacts (Tukker and Jansen 2006). Products are the physical embodiment of technology (Twiss, 1980). The creation of products, their use and their final disposal, are in the core of most economic activities. The past two decades have seen an unprecedented proliferation of high-tech products in the daily lives of most citizens in industrialised countries. Only a quarter of a century ago, the majority of people were mostly unaware of personal computers and mobile phones – nor would many have really missed such products. Since then, digital electronic products, infrastructures, and services have become ubiquitous elements of almost everybody's daily life. One can say that modern lifestyles without high-tech products have become inconceivable. The society and economy have become dependent on products that consist of scarce materials, run on electricity, and are very difficult to recycle. In other words, industrialised countries have become vulnerable to possible circumstances that may undermine the industry's capacity to create such products at acceptable costs. In addition, environmental pressures, such as global warming, energy security and depletion of natural resources have been recognised as severe risks for future developments (Stern, 2006; Bleischwitz et al. 2008).

The adverse impacts on the environment originate, for a large part, from the unintended (and sometimes unexpected) side effects of human production and consumption processes. The most important environment impacts span from resource depletion, man-made global warming and ecosystem damages, to particulate matter emissions that affect human health (UNEP, 2010). The human ecological footprint exceeded the Earth's carrying capacity in the late 1980s. By now, the ecological footprint of humankind on ecosystems has increased to a level that exceeds the earth's long-term capacity to carry our human civilisation. The World Resources Forum estimates that the environmental impacts of humankind's global economy have already surpassed the ecosphere's safety thresholds (WRF 2009). The planet is not able to sustain the mass-production and hyper-consumption in the long run. In other words, the current mode of technological development is not sustain'able' because "*Environmental degradation […] undermines future development progress*" and "*threatens all aspects of human well-being*" (UNEP, 2007). The World Resources Forum warns that "*we are losing ever more the freedom to shape the future of humanity*" if we continue the business-as-usual mode of economic growth (WRF, 2009). It follows, that the objective of sustainable development, or even better: of human economic activities in general, must be to reduce the environmental impacts of production and consumption to a level that does not jeopardise the earth's ability to sustain the present and future generations to satisfy their needs (WCED, 1987).

The well known I = PAT equation helps in understanding the influencing factors of economic activities and technology on the anthropogenic environmental impacts (Commoner, 1972):

$$I = P * A * T \qquad (1\text{-}1)$$

I	Environment impact
P	Population size
A	Affluence (consumption of products & services per person)
T	Technology efficiency (environmental impacts per product)

The factors of this equation are determined by multiple aspects. Besides population growth, it is increasing affluence (a desired development) and efficiency of technological systems that influence the global environmental impacts. The environmental impacts of products depend on how they are designed, produced, used and disposed of (Pennington et al. 2004; EC, 2009a). Technology has an ambivalent influence: on the one hand, the adverse side effects of technologies have increased the pressure on natural capital – causing affluence to decline. On the other hand, technological advances have tremendously increased affluence as they have made natural resources more accessible and more efficiently usable. Technology has thus the capacity to play a part of sustainable development, if the adverse side effects of its application are kept in check. Chertow (2001) underpins that now, "*a better understanding exists of how technology, combined with improved design, can greatly aid the quest for sustainability.*" Thereby, the emphasis is not on "*technological fixes*" (e.g. end-of-pipe technologies for pollution clean-up or waste recycling) but rather on the development of inherently sustainable technologies. Ehrenfeld (2008) however, warns, that a solely technocratic approach to sustainable technology development will not change the root causes of unsustainability. Innovation strategies that are built upon improvements of resource- or energy efficiency can mitigate environmental impacts in the short term only. The history of technology has shown that increasing consumption often outweighs efficiency gains at the technical level. The phenomenon is known as 'rebound effect' (Binswanger, 2001). Strategies for sustainable technological innovation must therefore also take into account the factor P and the factor A of the I=PAT equation. Pursuing improvements in the technical efficiency of products can only then contribute to a long-term relief from environmental impacts, if consumption patterns change.

The way in which products are designed has a large influence on their environmental performance (Frankl and Rubik, 2000). The design and engineering disciplines have therefore the potential to influence both aspects; the efficiency of technical artefacts (T) and the ways they are used and consumed. As design-engineers conceptualise and create new generations of products they do not only shape the technical and aesthetic properties of products. They also determine the future environmental impacts thereof as well as create the trajectories for the socio-economic uptake of new technologies. This action potential mandates the creative disciplines within the techno-scientific arena with an obligation to play a leading role in sustainable innovation (EC, 2003). The challenge is to adopt environmentally conscious design strategies concurrent with technological developments in order to avoid adverse environmental side effects before they materialise on a large scale.

That having been said, this dissertation attempts to contribute to knowledge on risk preventative design approaches for emerging technologies. On the basis of a case study approach, the research examines the potential side effects of smart textiles and derives strategies for eco-design for this new generation of technology. The thesis is addressed to those among the community of designers and engineers who perceive themselves as environmentally conscious pathfinders in the field of technological innovations.

1.2. Background

1.2.1. Innovation in the field of emerging technologies

A contemporary high-tech innovation trend favours the guiding idea to augment the functionality of products in order to make them smart. Smart products are envisioned to offer active services that go beyond the functionality of passive objects. Smartness is understood as an artefact's computational capacity that makes it is able to gather and to process information and to interact actively with its surroundings. The term 'smart' denotes the capacity of objects to sense and respond to external stimuli (depending on context of use and user interaction). Smart functions are frequently, but not exclusively, realised by embedding electronic components into formerly no-electronic products (Reade, 2010; Stylios, 2007). Other emerging technologies for smart products include engineered high-tech materials (such as phase change materials (PCM), shape memory materials, and nanotechnology etc.). Also RFID-based smart labels are examples of electronic devices, which are embedded into every day objects (such as packaging, or textiles).

The notion of 'emerging technology' refers to new technologies that are research and know-how intensive. Harper (2010) provides a preliminary characterisation of 'emerging technologies': They - 'arise from new or the innovative application of existing knowledge',
- 'lead to the rapid development of new capabilities',
- 'significant and long-lasting economic, social, political impacts expected',
- 'create new opportunities for and challenges to addressing global issues',
- 'have a disruptive potential to create entire industries'.

It is notable that the innovation system of smart products is crosscutting several domains of traditional as well as converging technology (Cho et al. 2010). Converging technologies are perceived as a master trend in technological innovations, including Nanotechnology, Biotechnology, Information and communication technology (ICT), and Cognitive sciences[1]. These technologies are expected to have a disruptive character, as they could trigger radical shifts in production and consumption patterns. The High Level Expert Group 'Foresighting the New Technology Wave', set up by the European commission (DG R), anticipated that „*Once all of us are living continuously in the pervasively artificial environment of ambient computing, smart materials and ubiquitous sensing, society will be confronted with far more frequent and deep transformations of people's and groups' self-understanding.*" (Nordmann, 2004, p3).

[1] The recently launched European flagship initiative on 'Future and Emerging Technologies (FET)' aims at advancing innovations of converging technologies in form of two multi-billion euro flagship projects ('Graphene' (nanotech) and 'Human Brain' (ICT-Neuroscience)). (EC, 2013)

The expert group advocates to "*promote sustainable development, environmental awareness, precautionary approaches*" in the innovation process of converging technologies (ibid, p 42).

Next to that, the European Commission identified a range of other 'Key Enabling Technologies'[2] that are strategically relevant for the European economy, including photonics, advanced materials, semiconductors (EC, 2009b). Other enabling technologies, such as ambient energy harvesting, human enhancement technologies, etc, are in the research and development pipeline and are expected to develop mass markets in future. These technologies, still being subjects of research and development, constitute a driver for technological innovations. They may become ubiquitous in daily life in the near future.

Far-reaching visions of smart technology are known as pervasive computing or the 'Internet of things' (Cook and Das, 2012). It has been anticipated that pervasive computing will enable future users to enjoy ICT-services whenever and wherever they wish. The notion of ubiquitous technologies stands for the idea of augmenting the function of daily life objects with computing power, which is provides by electronic devices that are unobtrusively integrated into these objects (Gerritsen et al. 2010). The technical base is information and communication technology (ICT) that is embedded or integrated in objects of daily life, which allow for the design of a new generation of products: cyber-physical systems (Horváth and Gerritsen, 2012). Computing enabled every-day products provide sophisticated type of smartness, so-called 'ambient intelligence' (Aarts and Encarnacao, 2006; Cho et al. 2010). They allow for extending the virtual world of digital computing and networking into the physical world of daily life. A wide range of day-to-day objects comes into question for that purpose, including garments, vehicles, buildings and structures of the built environment. The innovation system of wearable computing explores and develops new concepts of human-computer interaction in accordance to the concept of pervasive computing (Conti et al, 2012). Wearable computing is about the seamless integration of computing services into the user's the personal space by means of highly miniaturised, networked and body-mounted technology (Mann, 1998).

1.2.3. Innovations in the field of smart textiles

Textiles offer a convenient platform for mobile ICT devices as they are most ubiquitous in everyday life and because they are often used close the human body (Chan et al. 2012). Electronic textiles (e-textiles) form the hardware base of wearable technology and they may become a component of the Internet of things in future. They consist of textile embedded electronic components or ICT devices, which have to become miniaturised and flexible (e.g. laminated composite layers). Examples of high-tech components embedded in textile products are sensors, actuators, electronic devices, lightening elements and power generation & storage etc. Microsystems technology (MST) is a sophisticated technological approach (Linz, 2007). More detailed reviews of the physical properties, design aspects, and functions of e-textiles are provided in the sections 3.2, 5.3, and 7.7.2.

[2] Key enabling technologies are defined as "*knowledge intensive* [technologies] *and associated with high R&D intensity, rapid innovation cycles, high capital expenditure and highly skilled employment.*" (EC, 2012).

The term ‘smart textile’ refers to the function of a product (smartness) whereas the term e-textile refers to the technology (hardware) by which the smart functionality is realised. Figure 1-1 illustrates the definition of terminology used in this dissertation.

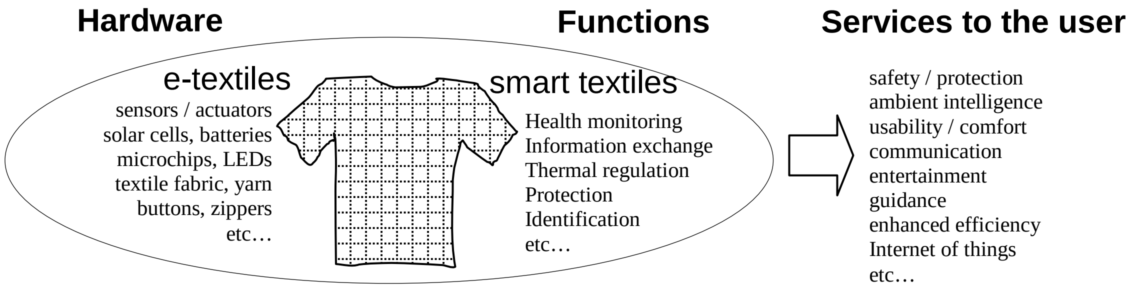

Figure 1-1: Smart textiles vs. electrically active textiles (e-textiles).

The innovation system of smart textiles is by and large a design-driven development process that follows a technology-push model (Lymberis, 2011).

The creative industry experiments with numerous technical concepts for textile-electronic integration. Design and development trends in the smart textiles innovation system point towards seamless integration of electronics and textiles. Visionary innovators distinguish three increasingly sophisticated generations of smart textiles (see section 3.2.1.):

1. Adoption: textiles as a platform for embedded electronic devices (e.g. pockets),
2. Integration: electronic devices are to be seamlessly incorporated (e.g. embroidered),
3. Combination: textile materials and structures with inherent electronic functionality (e.g. yarn transistor, fibre based circuits, photovoltaic fibres).

The applied R&D activities of smart textiles have seen an increasing attention throughout the last decade (Choi et al. 2011). Most of the enabling technologies and components of the first generation of smart textiles are readily accessible. Product developers rely on commoditised electronics components and combine them with textile products. Creative designers and experimenters have also handcrafted various functional components of textile electronics. By creating concepts for meaningful products they also create experiences with possible functions. This knowledge is a source of future design visions for the second and third generations of smart textiles. In this way, the contemporary design activities contribute to the technological advancement and prompt more fundamental research and development in the field of smart materials.

During the past couple of years, the technology underwent a hype cycle of high expectations. While technological advancements have repeatedly been advertised and exhibited at industry fairs and conferences the commercialisation of smart textile products is still pending. The smart textiles innovation cluster is still at a nascent stage of its formation as an industrial sector. A common branch-identity has not yet been formed. The innovation process in the smart textiles sector takes place in a very heterogeneous spectrum of enterprises, ranging from traditional producers of textile and electronic products to entrepreneurial high-tech SMEs (Small and Medium-sized Enterprises) (Dalsgaard and Jensen, 2011). As compared to other, more mature sectors, there is a relatively small number of companies active in commercialisation of smart textiles (less than 100 within the EU, according to the author's survey in 2011[3]). These SMEs occupy a large variety of highly specialised market niches. Competition takes place above all in terms of technological advancements and patent claims for enabling technologies. Competitive advantage emanates from design and realisation of meaningful products that provide their users with added value as compared to established technologies. In the future, the market proliferation of smart textiles will depend on the successful harnessing of economy of scale effects (Conti et al, 2012). This requires the production of e-textiles to become compatible with established industry-scale manufacturing processes of the textile sector.

Cloths with incorporated electronic devices (e.g. inbuilt mp3 player, solar cells) have been expected be at the verge of market entry. Several companies, large sport equipment producers as well as specialised SME, have successfully commercialised sports applications of smart textiles (Systex, 2012). Most of the few SMEs in the smart textiles sector are only beginning to commercialise their products. Their main attention is on technological improvements of the emerging technology as well as the creation of profitable markets for smart textile products. This fact contrasts to the fulsome expectations on market growth. The smart textiles sector has been estimated to grow rapidly, in particular in the market segments of sports and outdoor clothes, health care, and workwear. Various proprietary market intelligence reports forecast a rapid growth of the smart textile market in future. The global market volume of smart fabrics and interactive textiles is expected to reach $1.8 billion by 2015[4]. Market observers foresee the market of wearable electronics to be set to "*explode*" (Harper, 2012). The hype is fuelled due to the assumption that the emerging technology will have disruptive influence on consumption patterns in the consumers market (Textiles Intelligence, 2012). Smart textiles in the market segments of sports, wellness and fitness are closest to the market introduction (Rossi and Paradiso, 2011). Thus far however, the smart textile technology has not made breakthrough on the mass consumer markets. Figure 1-2 displays a typical technology life cycle model and indicates the current situation of the smart textiles sector.

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[3] LCA-to-go Technical report on needs and demands of SMEs. Available online: www.lca2go.eu

[4] http://www.transparencymarketresearch.com/smart-fabrics-and-interactive-textiles-market.html

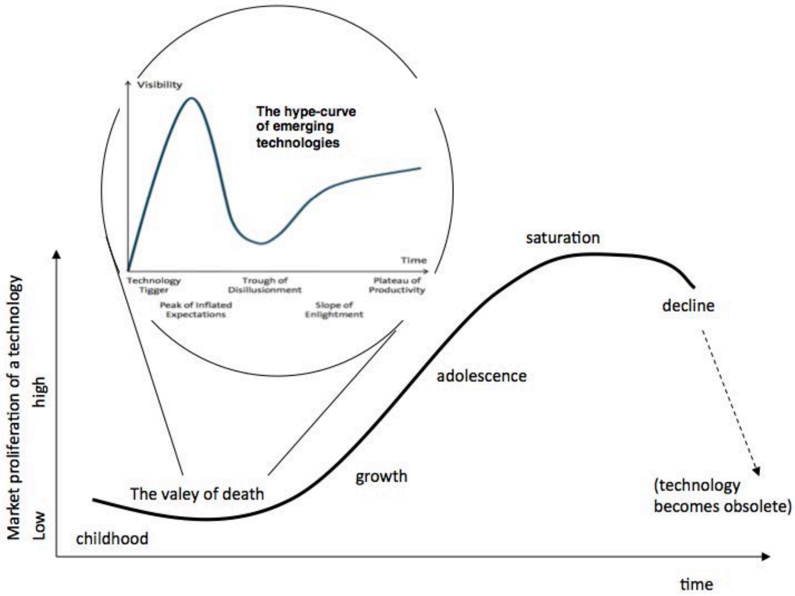

Figure 1-2: The stylized technology life cycle model. The inset illustrates the hype-cycle of public attention at the early stages of high-tech innovations. Source: adopted from (Grübler, 2003; Linden and Fenn, 2003).

The future success of the smart textiles sector depends on the overall economic situation as much as the sector's ability to overcome prevailing shortcomings in the technical performance of contemporary smart textile prototypes (Stylios, 2007). Entrepreneurs in the smart textile sector see good opportunities to overcome the current problems by progress of technological innovation. The new generation of smart textile products is currently in a 'fuzzy-front-end' stage of the product innovation process. It is characterised by the transition from technological concepts (enabling technologies) towards the design of competitive products. At the moment, "*Technologies are just not mature enough for textile companies to consider them as standard components*" (Dalsgaard, 2010). In future, it will be crucial for the creative industry to conceive smart textiles that provide their users with meaningful functions. Smart textiles are set to enter the next stage of the technology life (mass commoditisation) once that they offer a sufficient consumer added value. The fate of a more matured technology was exemplified by mobile communication technology (see section 3.6.).

1.2.4. Policy frameworks and innovation strategies

1.2.4.1. European innovation strategies

Technological innovations are often heralded as a key to the future it is perceived as a driver for growth and prosperity. Innovations are seen as a cornerstone for the further progress of knowledge-based and resource efficient, greener, and more competitive economy. For this reason, the European Union has placed knowledge and innovation at the core of its 'Europe 2020 strategy for growth and jobs' so as to attain a "smart[5], sustainable[6] and inclusive econo-

[5] 'Smart' refers to three key elements: Education, Research/innovation for new products/services, and Digital society (using ICT) (EC, 2010).

my" (EC, 2010). As a means to foster innovations in the European Union, the Commission has set up seven flagship initiatives. Four of them are particularly relevant as a policy framework for the smart textiles sector.

- The "Innovation Union" flagship initiative aims creating growth and jobs by improving the conversion process from innovative ideas into products and services.
- "A digital agenda for Europe" will increase the access to high-speed Internet infrastructure and competitive digital services. It aims at intensifying the use of ICTs for energy saving, support of ageing citizens, health services and better public services.
- The "Resource efficient Europe" flagship initiative aims at decoupling economic growth from the resources consumption. It also supports the innovation of low carbon and renewable energy technologies.
- The "industrial policy for the globalisation era" aims at boosting growth and jobs by strengthen European SMEs and creating the framework conditions for sector-specific actions, in such innovation in advanced manufacturing technologies.

Within the 'Europe 2020' framework, the European Commission implements a variety of policy actions to enforce the strategic goal of smart and sustainable growth. The following strategic actions areas (inter alia) prepare the stage for sustainable high-tech innovations in future:

- Improving the energy and resource efficiency of production and consumption as well as the sustainable management of domestic raw materials.
- Support of low-carbon technologies and more effective recycling technologies
- Development of environmentally friendly technologies and production methods, which help reducing and preventing environmental degradation and promoting their adoption.
- Setting up interoperability standards in the ICT sector and improving standard setting procedures will speed-up the adoption of key enabling technologies. Supporting of open platforms
- Development of new generations of web-based applications and services.
- Supporting young innovative SMEs and crowd-sourcing for entrepreneurial ideas to grow sustainable businesses.

The creative industry is perceived to be a crucial contributor to the long-term success of the above mentioned strategic action areas. The European Commission purposes to strengthen the role of the creative industry in the innovation process by embedding this discipline more closely in innovation programmes and business incubators. Design is seen as a tool for innovations that helps in harnessing prosperity and wellbeing across Europe. For that purpose, it is aimed to support top design expertise and to strengthen design literacy of the European citizens. The Design Leadership Board's has formulated recommendations to the European Commission to strengthen Europe's design innovation capabilities (EC, 2012b). It is stressed "*Design is considered as a sector in its own right*" that "*In addition to its economic benefits, also encompasses sustainable and responsible behaviour contributing positively to an innovative society and improved quality of life*" (ibid. p15). The 21 proposed actions aim at promot-

[6] 'Sustainable growth' refers to a competitive resource efficient low-carbon economy, Environmental protection, Development of new green technologies and production methods, among other aspects (EC, 2010).

ing design excellence in the European industry, in particular SMEs. Sustainable design is highlighted as a key success factor as it can "*further differentiate Europe on the world stage*" in that "*sophisticated, sustainable products, raise awareness of the importance of sustainable development and increase respect for design's role in innovation and technology*" (ibid. p34). In summary, it appears that there is an increasing awareness for the role of design in the context of sustainable technological innovations and this will have impacts on future developments in the high-tech sector.

1.2.4.2. Research and innovation programmes in the field of smart textiles

Various publicly founded innovation programmes at European and national scale have been implemented to stimulate innovation in the smart textiles sector. SMEs have been taken on board of these programmes to foster technological competitiveness of European economy. Next to the number of active SMEs in this field the innovativeness can be measured by the existence of national innovation programmes addressing this technology. Public-private innovation clusters exist in Germany (MST Smart Textil) and in Scandinavian countries[7] (Sweden, Denmark) in addition to EU-FP6 (completed)[8] and FP7 projects (SYSTEX)[9] as well as the Interreg IIIC scheme TeTRInno SmarTEX (completed)[10]. Currently, R&D projects in the field of smart textiles are funded under the umbrella of the Digital Agenda for Europe[11]. These are: PLACE-it (stretchable electronics and light sources based on fabric and foil) and PASTA (Integrating Platform for Advanced Smart Textile Applications).

1.3. Environmental risks of emerging technologies

1.3.1. Lessons learnt from innovations of the past

The history of technological innovation is rich of examples where new technologies proliferated at the mass markets before their adverse side effects on environmental health and safety were properly mitigated (EEA, 2001). Unintended impacts of new technologies may not become evident until several years after their market diffusion. In many cases, there had been early warnings on possible environmental risks but they were ignored because the level of scientific evidence was weak in the beginning. The uncertainty regarding possible risks hindered the implementation of risk preventative measures in the design phase of emerging products. Only after the technology was up-scaled at the mass markets the adverse impacts have become visible in form of environmental, health, and social impacts. The mass application of products amplified the adverse side effects of technologies and caused a widespread propagation of the impacts in the environment. In the worst cases, the adverse side effects of technologies have damaged the health of many people due to occupational exposure to hazardous substances (e.g. asbestos, PCBs), exposure to contaminated water or food (e.g. heavy metals), or environmental pollution and waste (Schmid et al. 2000). For example the e-waste problem

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[7] http://www.smarttextiles.se; http://www.futuretextiles.dk
[8] e.g. WearIT@work project; http://www.wearitatwork.com
[9] http://www.systex.org
[10] http://www.mateo.ntc.zcu.cz/aboutproject.php
[11] http://cordis.europa.eu/fp7/ict/micro-nanosystems/projects-sfit_en.html

has emerged as a global sustainability problem (Puckett et al. 2002; Puckett et al. 2005). Original Equipment Manufacturers (OEM) of the electronics industry have recently started to design products in ways, which hinder the replacement of integrated batteries and effectively prohibits repair and refurbishment. In consequence, this accelerates the obsolescence of electronic products and aggravates the e-waste problems.

Taking the example of Polychlorinated biphenyls (PCBs), the European Environment Agency illustrates what can happen if an enabling technology is widely used for technical applications without assessing the risks toughly (EEA, 2001). Initially, it was assumed that sealed containment of PCBs in products was sufficient to control the hazard of the substance. However, it was overlooked that PCBs can be released from badly maintained equipment during the use phase or during disposal and recycling processes. The possibility of PCB contamination is one of the reasons why electronic products, being once considered high-tech, are considered to be hazardous waste at the end of their life cycle (Leung et al. 2006). Risks preventative measures were taken too late although there were warning signs about harmful effects for human health and environment. However, the scientific evidence regarding the risks was considered to be insufficient for action. It was not until the environmental and health impacts of PCBs reached a tremendous dimension that the use of PCBs in products was eventually prohibited[12]. The EEA concludes that earlier control of PCBs would "*have resulted in a more manageable, less costly problem than we are faced with today*" (EEA 2001, p.71).

Lessons learnt from past innovation cycles suggest that the control the possible risks would have been easier during the early stage of technology proliferation. The mass application of a technology in consumer products can be taken as an indicator for the possible risk to have more widespread impacts on environment and human health. However, the uncertainty regarding the determinants of possible risks often hindered the implementation of preventative measures. The EEA warns that ignorance or uncertainty about possible risks must mot be mistaken for absence of risks. In order to reduce 'blind spots' in risk appraisal research into early warnings ought to be undertaken concurrent to the technological innovation process. A precautionary innovation strategy would promote the development of "*more robust, diverse and adaptable technologies [ ] so as to minimise the costs of surprises and maximise the benefits of innovation*" (EEA 2001, p.194).

1.3.2. Previous research findings

1.3.2.1. Technology assessment of emerging technologies

The research reported in this dissertation was undertaken in continuation of the author's prior research along the veins of the above-mentioned recommendations of the EEA. In the course of several technology assessments studies the author investigated the interdependence of technological innovations and sustainability impacts. The experiences from these studies influenced the choice of the current research topic. This section recapitulates selected papers

[12] The Stockholm Convention on Persistent Organic Pollutants. (2001). http://chm.pops.int

(authored or co-authored by the author of this dissertation) that are thematically relevant for this dissertation but not enclosed into it.

A technology assessment on pervasive computing identified and evaluated the potential risks on human health and the environment (Hilty, Som and Köhler, 2004). The ex ante assessment of an emerging technology encounters two types of uncertainties: First, the nature of side effects and their causal links to adverse impacts on safeguard subjects. Second, the extent of the impacts depends on how the technology will be taken up by society in future. It is shown that some adverse impacts of the new technology can amplify well known impacts environment, human health, and society, such as: increasing power consumption, consumption of scarce resources, growing e-waste streams, and exposure to non-ionizing radiation (Köhler and Som, 2005). From the viewpoint of sustainability, the response to potential risks ought to be guided by the precautionary principle (Som, Hilty and Köhler, 2009). Is applied to the typical situation at the early innovation stage when prospective risks of the technology are difficult to assess due to scientific and socio-economic uncertainty. Preventative measures should be implemented already at an early stage of technology development to avoid socio-economically irreversible risks.

Emerging nanotechnologies inspire product designers to take advantage of the outstanding properties of nanotechnology. At the same time, there is concern about the Environmental and health implications of engineered nano-particles. The human health and environmental risks of carbon nanotubes (CNT), for instance, are influenced by the likelihood of exposure to them (Köhler and Som, 2008). The exposure depends on the stability of their integration into products and the ways in which these nano-particles could be liberated. It was found that the release of CNT depends firstly on how they are incorporated into the products, secondly on the design of the products, and thirdly on the way in which the products are treated during their life cycle. This may pose occupational safety problems for the recycling industry since these businesses are often unaware of the risk. The proactive management of prospective risks depends much on the awareness and risk attitudes of those who develop new products based on nanotechnology (Köhler and Som, 2008). Lessons learnt from past experiences with unintended side effects of emerging technologies suggest that innovators have possibilities to implement risk prevention strategies. A voluntary commitment within industry to implement adequate safety standards of nano-products is as important as open and transparent risk communication. The prevention of potential risks is a key strategy for businesses that aim at successful commercialisation of nanotechnology-based products.

A technology assessment study on the end-of-life implications of electronic textiles established the preparatory research of this dissertation (Köhler 2008). The expected properties of e-textiles were evaluated against the contemporary state of the art in recycling and disposal schemes for electronic waste and old textiles. The assessment indicated that e-textiles could aggravate existing e-waste problems once that these products are mass-produced, consumed and then disposed of. Further, innovators from European research institutes and enterprises were asked what waste prevention measures are adopted in the technology development process. The survey results indicated that most innovators paid little attention to potential end-of-life impacts of e-textiles. As a conclusion, the study mapped further research needs in regard to viable eco-design strategies applicable in the innovation process of e-textiles.

1.4. Risk preventative innovation strategies

1.4.1. Prevention as a strategy of ex ante risk treatment

Risks are understood as the effect of uncertainty on objectives and are expressed as the combination of the severity of impacts and their likelihood of occurrence (ISO 31000). In other words, the prospective environmental impacts of smart textiles can be regarded as the possible deviation from the objective of environmental sustainability. This objective is in the core of European innovation strategies: Sustainable growth aims at "*promoting a more resource efficient, greener and more competitive economy*" (EC, 2010). Hence, there is a need to control possible adverse side effects of innovative technologies that could undermine the objective of sustainable innovation. In industry, risk management procedures are usually implemented at the end of the feasibility phase of the innovation process (Helman, 2013). Mitigating such risks at the transition stage from product development to production ramp-up is the business-as-usual approach. By then, the risks are manageable because the uncertainty about product properties, the manufacturing processes, and other aspects is tangible. However, the management of product related environmental risks is not a default part of corporate risk-diagnosing methods (RDM), which focus at the following risk domains: technical, legal, market, finance and operations. In the context of emerging technologies, the possible environmental side effects remain intangible due to the uncertainty about the possible damage on environmental safeguard subjects and the order of magnitude at which they might occur. The risk management framework ISO 31000:2009 suggests the following strategies for the treatment of risks:

a) "*avoiding the risk by deciding not to start or continue with the activity that gives rise to the risk*"
b) "*taking or increasing risk in order to pursue an opportunity*";
c) "*removing the risk source*";
d) "*changing the likelihood and changing the consequences*";
e) "*sharing the risk with another party or parties*";
f) "*retaining the risk by informed decision*".

Strategy b) represents the business-as-usual mode of innovations, which accepts environmental risks in the pursuit of technological and business opportunities. Section 1.1 has detailed that a risk-taking strategy of technological innovations can jeopardise of the objective of sustainable growth. The strategy a) is a very risk averse option that has often been dismissed by technology developers, who argue that it can result in a roadblock to innovations. However, in cases where technologies caused severe and irreversible risks it has been endorsed by international treaties and national legislations. Examples are the Montreal Protocol (the ban of chemicals depleting the ozone layer) (UNEP, 2007) and the European RoHS directive (imposing a ban of certain hazardous substances in electronic products) (EC, 2002). The strategies c), d), e) and f) can be regarded a risk preventative innovation strategies in the sense of the precautionary principle. It suggests mitigating risks in an anticipatory manner, even if the risk factors are uncertain or intangible from the contemporary perspective.

1.4.2. The role of design in risk prevention

Design decisions taken in the product design stage determine the environmental impacts of a product over its whole life cycle (Caduff, 1999). Later on, during the subsequent life cycle stages, including manufacturing, use and disposal, the ability to adjust environmentally relevant properties and functions of products is lower. It is therefore relevant to pay special attention to the role of the product design within the innovation process of emerging technologies.

Twiss (1980) describes the technological innovation as a stepwise conversion process from scientific knowledge into a business purpose. Four principal stages of the innovation process can be distinguished (Figure 1-3): the first stage is fundamental research (creation of scientific knowledge and know-how); the second stage is applied R&D (transforming scientific knowledge into technical concepts); the third step is industrial product design and engineering; and the fourth step is production ramp-up (establishing competitive industrial manufacturing). In a first conversion step, the scientific knowledge is transformed into an invention (a technical concept) matching customer needs. It is then the design process, which transforms technical concepts into meaningful products. Creativity is an indispensable attribute of the design stage.

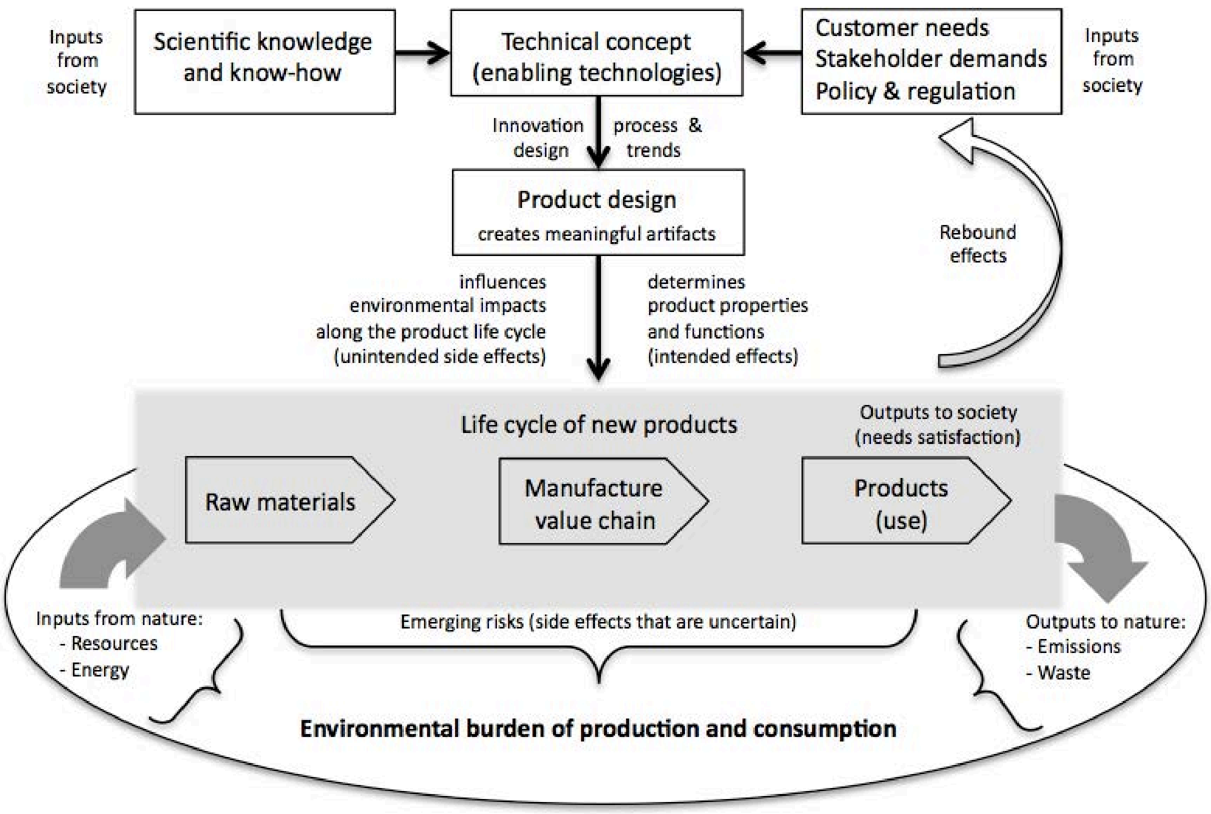
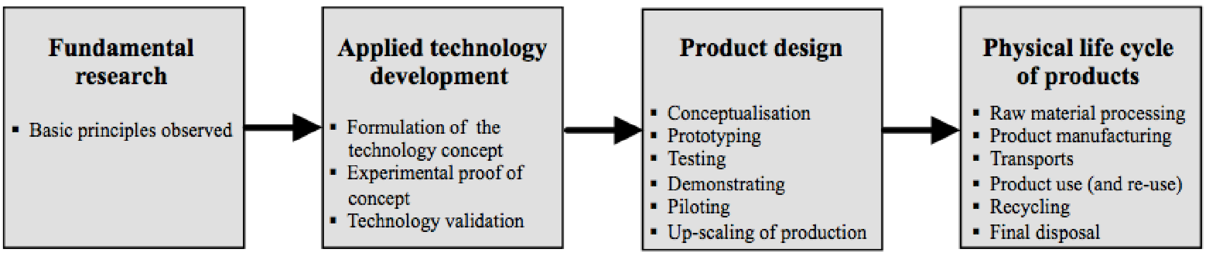


Figure 1-3: The role of design in the innovation process and its influence on product life cycles. Source: adopted and amended from (Twiss, 1980).

The intended output of the design process are concepts for the production of commercially competitive products that satisfy the customers' needs. Innovations in the field of design combine not only technological aspects but also styling, human factors, marketing, and society (Reinders, 2013). Innovation constitutes a value creation process that often runs in iterative cycles. The Delft Innovation Model describes a circular innovation process from a company perspective and distinguishes five stages: "*1. Product Use, 2. Strategy Formulation, 3. Design Brief Formulation, 4. Development, 5. Market Introduction*" (Bujis, 2012). In this model, the innovators are part of a multi-disciplinary team, the "*Multi-X-Team*", which leads the creative process, starting from strategy formulation, over to idea generation and actual product development, up to the market introduction. The innovation cycles are the faster the younger the emerging industry is. The early phases of product innovations are characterised by experimental product designs and trial and error product launches. A product generation becomes inflexible against fundamental changes of basic design features as soon as the innovation process enters the stage of competitive manufacturing. It is common, that high-tech products are produced in capital-intensive industrial value chains, which are most profitable under the economy of scale paradigm.

The design stage has a large influence not only on the properties and functions of products. In addition it triggers new needs and demands in that it rouses the consumer's expectations for new innovative products. New product generations render the previous ones increasingly unfashionable (so called psychological obsolescence) or incompatible to the state of the art technosphere (so-called progressive obsolescence) (Slade, 2006). In a way, design has a trend-setting influence on the consumers' and thereby induces new innovation cycles. Twiss (1980) emphasises that "*technology is responsible for many of the most important changes in our society*". This leads to a positive feedback loop in the innovation cycle.

The innovation process illustrated in Figure 1-3 can be extended with a schematic representation of the production and consumption processes (raw material processing, product manufacturing, product use phase, and end-of-life phase). The environmental burden of products includes all inputs from nature and all emissions (including waste) throughout the life cycle of physical products[13]. In addition, the production and consumption of emerging technologies can entail undesired environmental side effects that remain uncertain (risks) in the beginning. For the further discussion, the innovation model displayed in Figure 1-3 is simplified in order to disentangle the links between design decisions and environmental implications of emerging technologies. Figure 1-4 displays an incremental innovation model, based on the decision framework that was adopted from the innovation policy of the European Union (EC, 2012a).



[13] The physical product life cycle (raw material, production, use, disposal) is not to be confused with the economic product life cycle (introduction, growth, maturity, decline).

Figure 1-4: Simplified sequential innovation model for emerging technologies. Adopted from (EC, 2012a) [14]

Innovation in the high-tech sector is usually the result of a technology-push process as displayed in Figure 1-4. Such a simplification is reasonable because, in many cases, basic techno-scientific inventions precede product innovations, which in turn precedes the market dispersion phase of a technology. Product innovations are often triggered by inventions in materials sciences (e.g. engineered nano-particles), engineering sciences (micro-system technologies), or computer technologies (e.g. new data processing mechanisms). This causal sequence holds true notwithstanding the fact that technological innovations happen often in an iterative process. Product innovations can also be triggered when sophisticated manufacturing technologies (e.g. 3-D printing, laser cutting) become economically more accessible for a broader range of innovators. The advancement from a technical concept to a market-ready technology is typically bound to incremental R&D and design cycles, which can take many years. Even disruptive technologies, such as nanotechnology, remain in a nascent stage for quite a while before they are ready to be transformed into competitive products.

During the innovation process, a plethora of design decisions are made, determining the environmental performance of a whole generation of technical artefacts. Noteworthy, that the knowledge about the properties of the future product is very fuzzy in the beginning. At the same time, the freedom of design (the range of possible choices a product developer can take) is largest. In this situation, known as the Fuzzy front End of Innovation (FEI) (Koen et al. 2001), it would be relatively easy to change certain product properties of functions that may, in the later run, become the source of undesired side effects. In other words, the modification costs are low and this eases the implementation of risk prevention measures. However, at the early stage of product design exists little knowledge about the possible side effects and their causes. This state of uncertainty hampers the implementation of risk prevention measures. Risk relevant knowledge may become more available later in the design process. But the technology developer's freedom to change fundamental design aspects diminishes and the modification costs increase. Figure 1-5 illustrates this fundamental trade-off.

The knowledge about the product properties and functions increases as a product takes shape in the course of the design process. The creation of products related knowledge is the very nature of industrial design. Designers solve problem by synthesis rather than by scientific analysis (Cross, 2006). In a typical design process, the time available for analysis is a scarce resource. The creation of design knowledge is therefore limited to product related aspects whereas the co-creation of knowledge about the possible environmental risks of the product is restrained. In a business-as-usual procedure, products are often commercialised without their environmental side effects being toughly evaluated. This knowledge gap indicates a shortfall in risk management of innovation processes (figure 1-5).

[14] In the literature there are various cyclic models of product innovation systems that show more complex interrelations of the different innovation stages (e.g. Bujis, 2012; Berkhout, 2006). However, these models usually take an actor-centred or a regional perspective, which appears less practical for the analysis of environmental risks along a technology life cycle.

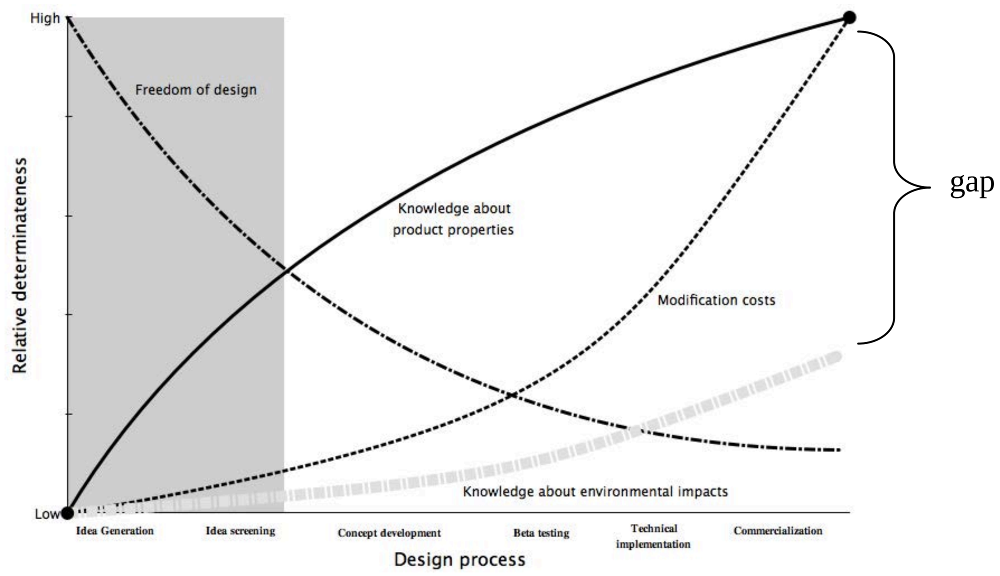


Figure 1-5: Schematic diagram of the relationship between design freedom and the knowledge about product properties during the product design process. The grey shade indicated the Fuzzy Front End (Koen et al. 2001). Source: figure adopted from (Kengpol and Boonkanit, 2011)

In the bigger context of the technology innovation process, this trade-off refers to the "*dilemma of control*'' (Collingridge, 1980), which is better known as the Collingridge Dilemma. It refers to the problem of making informed decisions at the early stage of any technology development process. Likewise to the FFE of design, the range of possible technological choices is substantial at the early innovation stage and the opportunities for choosing and influencing innovation trajectories are best (Dewulf, 2013). However, it is difficult to steer technology developments towards sustainable innovation at a time when little knowledge exists about possible risks. Despite the good freedom of choice among immature technical concepts, there is usually insufficient knowledge available to select the more sustainable alternative.

During the adolescent or mature stages of a technology life cycle the variety of options wanes due to an entrenchment of previously taken choices. Technologies (such as electronics) usually undergo a process of commoditization before they become ready to be commercialised. Commoditization can be understood as a selection process that reinforces certain technical and socio-economic particularities of a technology. Moreover, society and the economy adapts to a technology. The typically large investments during the R&D process are attributed to the outcome of the innovation processes (e.g. in form of patents). Once technologically innovative, but unsustainable products reach large market volumes enterprises may be hindered in mitigating an unsustainable development trajectory (Rohner and Boutellier, 2008).

The entrenchment of a technology due to commoditization can thus result in 'lock-in effects ' that render corrective action difficult and slow. This makes established technologies quite persistent against subsequent redesign of products or functions. Figure 1-6 illustrates the 'Collingridge dilemma' as the increase of risk mitigation costs during the product design phase of the technological innovation process.

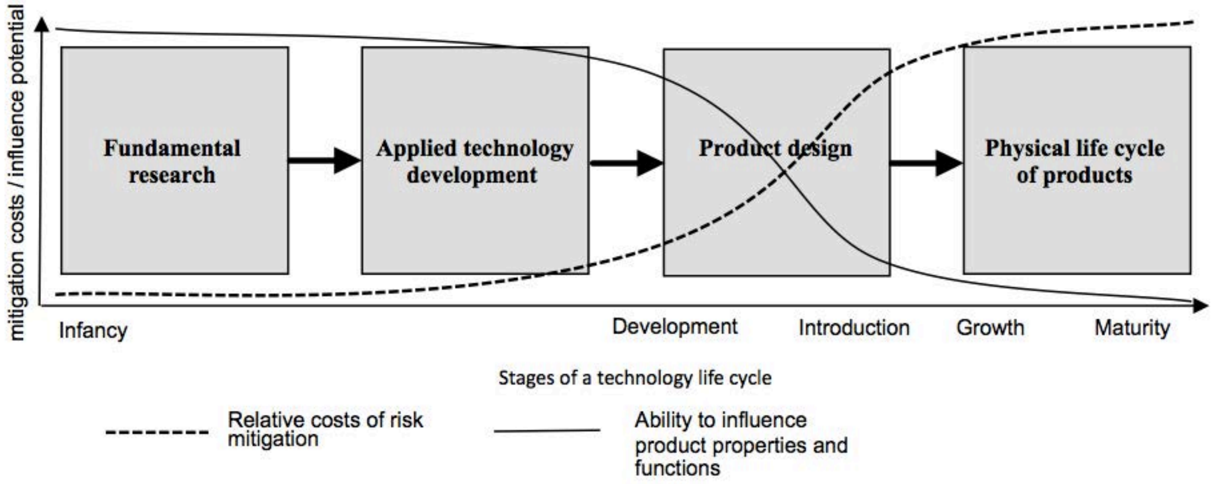


Figure 1-6: Framework for risk prevention in the innovation process (schematic diagram)

The selection of enabling technologies that will essentially determine the properties of future products happens in the product design stage. Key decision aspects include the specification of product functions as well as the selection of materials, size/shape, inbuilt software, and communication protocols. Each of these design choices narrows the design freedom of subsequent stages. At the same time, it becomes more and more costly to revise design decisions, for instance if unexpected side effects require a re-design. This lock-in in previously determined properties and functions of a product generation is reinforced after the market launch, and even more when the technology has pervaded widely within social and economic systems.

Collingridge (1980) suggests tackling the dilemma of technological decisions under conditions of uncertainty by systematically collecting and monitoring current knowledge on the potential benefits and risks of the technology. Factors, which would increase the social costs of inappropriate development trajectories, must be identified and avoided from the very beginning. Additionally, he proposes maintaining as much flexibility in the development process as possible so as to delay path dependencies in innovation (entrenchment). Keeping the design process of products open for sustainable alternatives (technical, materials, functions) can help to delay the occurrence of path dependencies.

Knot et al. (2001) delineate three flexibility strategies that aim at avoiding the entrenchment of unsustainable trajectories in the innovation process of technological systems. The first strategy is the formulation of robust technological options that prevail in different scenarios of technological futures. That means, the chosen innovation trajectory should be resilient under the condition of emerging risks as well as changing socio-economic and cultural circumstances. This flexibility is the second strategy and aims at increasing the adaptability of design options of a technology. The design process should "*leave the specific features of the product open to be determined later on*" (ibid, p.338). The third strategy is variety of technological alternatives, which support the same functions. Variety includes also non-technical alternatives, such as organisational and management schemes or policy measures. In this sense, design has the possibility to do more than determining product properties. The influence potential of design extends into the area of consumer behaviour and user acceptance of alternatives.

The product design stage has a decisive position in the innovation process as Figure 1-6 illustrates. Therefore, it matters to commence risk preventative measures right at the beginning of this stage. The next section introduces environmentally conscious product design as a framework for risk preventative technology development.

1.5. Environmentally conscious design as a risk prevention approach

1.5.1. State of the art in eco-design

Environmentally conscious product design (eco-design), also known as Design for Environment (DfE), is the "*systematic consideration of design performance with respect to environmental, health, safety and sustainability objectives over the full product and process life cycle*" (Fiksel, 2009, p6). The technical report ISO/TR 14062:2002 standardises the procedure how to consider environmental aspects in the product design and development process (ISO, 2002). Eco-design is an important pillar of the European Union's strategy on Integrated Product Policy (IPP) (EC, 2009a). IPP roots upon a preventative concept in that it stimulates eco-design action to be taken in the design stage of products. In the IPP context, the application of life-cycle thinking is considered a crucial element in the design phase of products (EC, 2003). Eco-design principles and tools, such as life cycle assessment (LCA), provide assistance for technology designers to reduce life cycle wide environmental impacts. The eco-design of products typically addresses a variety of aspects that can have a large influence on a product's eco-efficiency (Bovea and Pérez-Belis, 2012). It has been established that four types of eco-design can be distinguished, depending on the scope of influence on technical systems (Brezet, 1997):

1) Product improvement (addressing the direct properties of a product, e.g. materials)
2) Product redesign (changing the functional components of an existing product concept)
3) Function innovation (revision of the functional concept in which the product is used)
4) System innovation (applying new concepts at a systemic level to provide functions in radical new ways).

These eco-design approached differ in regard to the achievable efficiency gain. While the improvement of direct properties and functions of a product appears easiest to implement (picking the low hanging fruits) the possible improvement potential is low. Direct eco-design aspects include the selection of materials (e.g. using non-toxic substances, recyclable materials), the choice of production processes (e.g. in regard to waste and emissions), the determination of the products' energy demand during the use-phase, as well as its end-of-life treatment (i.e. repair and recycling) (Allenby and Fullerton, 1991). Ljungberg (2007) presents models for the selection of materials with regard to their sustainability characterisation and reviews strategies for more efficient use of materials (including dematerialisation and recycling). Recently, the increasing scarcity of certain critical raw materials that are indispensable for the production of modern high-tech products has also moved into the consideration of sustainable design (Tischner and Hora, 2012) (see chapter 7). More holistic eco-design strategies centre around the function of products and their influences on the environmental relevant behaviour of their users. For one, the functions of modern products can help their users saving energy or avoiding unnecessary travel. Moreover, the functions of modern information and communication technologies (ICT) offer opportunities to substitute virtual services for physical products (dematerialisation) (Plepys, 2004). The greatest efficiency gains are possible by innovating the production and consumption processes at a systemic level (Brezet, 1997). This is a long-term eco-design strategy and should be implemented at an early stage of product innovation, for instance by greening the design brief (Dewulf, 2003). This document concludes the fuzzy front end of innovation and can set the subsequent product development process on an environmentally benign track. However, Dewulf also observes „*the available ecodesign support tools are primarily useful in late stages of a design process*“. Wever and Boks (2007) examine the suitability of contemporary Design for Sustainability methods at the fuzzy front end of design and conclude that additional options for sustainable innovations exist at this early design stage. They motivate further research into the extension of existing eco-design tools to make them better applicable in practice. Moreover, integrated sustainability education of design engineering students should address the willingness and ability of designers to implement eco-design from the beginning.

The following two sections review the policy and regulatory frameworks of eco-design within the previously distinct sectors of electronic industry and textile industry.

1.5.1.1. Electronic eco-design

The traditional objectives of eco-design aim at optimisation of a products' environmental performance (efficiency). The electronics industry has developed the concept of 'Applied Eco-Design' (Stevels, 2007). Design rules, checklists and standards support technology designers when taking design decisions. They help in ensuring legal compliance (the defensive approach) of their products and enhancing the eco-value (the proactive approach). Tischner and Hora (2012) provide a comprehensive review of best-practice eco-design rules in the electronic sector. The international standard ECMA-341 can be regarded a reference for environmentally conscious design in the ICT sector. It offers a collection of eco-design rules for ICT-manufacturer and leads them to assume life cycle thinking in product design (ECMA, 2008).

Pioneers in green electronics design have noted that each new product development requires tailored life-cycle analysis (LCA) or at least environmental benchmarking. LCA tools have been developed and tested to support the design of 'Green Electronics' (Griese et al. 2003; Mueller et al. 2004). Benchmarking methods have been applied as a basis of strategic eco-design decision support (Wever et al. 2007). There exist also design principles and assessment methods specifically addressing the end-of-life phase of electronic products (Hesselbach et al. 2007). With regard to recycling of e-waste, quotes for environmentally weighted recyclability factors (QWERTY) were developed by Huisman et al. (2003). This concept allows for adequate implementation of the waste prevention principle in the design phase of electronic consumer products. The industry is starting to become more aware of the need to design electronics for intensified recycling of critical materials (Bloch and Quella, 2011).

However, the eco-design approaches in the electronic sector have still a large improvement potential in terms of industrial implementation (Schischke et al. 2006). Environmental design criteria seem to play an inferior role in the development process of most commoditised electronic products (Knight and Jenkins, 2009). Boks (2006) explored the barriers and success factors for eco-design implementation in major multinational companies of the electronics sector. He found that the insufficient cooperation and organisational complexities are the major obstacles to the dissemination of eco-design. Eco-design proponents seem to have difficulties communicating with product designers about the need and strategy of sustainable technology development.

In the electronics sector, the eco-design of products is strongly influenced due to regulatory requirements (Bloch and Quella, 2011). The European WEEE directive (EC, 2012c) imposes extended producer responsibility (EPR) to manufacturers of electric or electronic equipments (EEE). This means, the producer of EEE is in charge for the end-of-life management of waste products. The Waste Framework Directive 2008/98/EC specifies a hierarchy of waste management strategies where waste prevention has priority over reuse, recycling, other recovery, energy recovery; and disposal. According to this regulation, extended producer responsibility is also imposed to the developers of new products (not only the producer) (EC, 2008). The aim of these regulations is to encourage industry to implement waste prevention measures already in the design stage of EEE. Focus areas of policy frameworks for electronic eco-design encompass the following aspects:

A) Design for recycling (DfR) is encouraged by the European WEEE directive indirectly through extended producer responsibility (EPR principle).

B) Phasing out certain hazardous substances from EEE as stipulated by the European RoHS directive (EC, 2002). These substances are the following: lead (Pb), mercury (Hg), cadmium (Cd), hexavalent chromium (Cr^{6+}), poly-brominated biphenyls (PBB), and polybrominated diphenylether (PBDE)). The RoHS directive has resulted in a reduction of the toxic load of commoditised electronic components (Deubzer, 2012). The regulation had a global impact on the electronics sector although it is legally binding in the EU member countries only (Chancerel and Schischke, 2011).

C) Design of energy efficient products as required by the European eco-design directive on energy related products (ErP) (EC, 2009). The ErP directive focuses at the use phase and is lacking the full product life cycle perspective (Nissen, 2012). Moreover, the ErP directive is barely applicable in the development of emerging technologies since the scope of this regulation is limited to:

- product groups with large sales volume (market significance),
- relative certainty on environmental impact that is addressed,
- clear improvement potential of eco-design measures.

These strict requirements deter the application of ErP in the development process of smart textiles because these products have not (yet) a high sales volume. There is also little certainty about the effectiveness of measures aiming at environmental improvements.

As yet, e-textiles are not explicitly considered to fall into the range of products that are addressed by the directives mentioned above. However, it appears likely that they will be included into the coverage of regulation (e.g. future recasts of the WEEE Directive) if large quantities of them arrive in the waste stream. In this case EPR would be imposed to developers and manufacturers of e-textiles. Enterprises that pioneer the development of smart textiles may take this scenario into account when developing long-term business strategies.

1.5.1.2. Eco-design and eco-labelling approaches in the textile sector

In the textile and apparel sector, eco-design addresses above all the environmental impacts throughout the value chain of fibre production and textile manufacturing (Tobler-Rohr, 2011). Eco-design approaches are mostly related to the reduction of hazardous chemicals in consumer products. Foremost attention has been paid to reduction of chemical (e.g. dyes, bleach etc.), using water more efficiently as well as wastewater purification. The textile industry has undertaken efforts to prevent environmental pollution of manufacturing processes, mainly in terms of environmental management. Moreover, the apparel industry has increasingly responded to consumer demand for 'Green Textiles'. Clothing ought to be free of toxic residues from fibre production (e.g. pesticides) and fabric manufacturing processes (e.g. bleaching agents, dyestuff, etc.). There is a trend towards use of organic cotton and other natural fibres that are produced in compliance with certain sustainability standards.

Design for green textiles has been focusing on greening the supply chain (elimination of production steps that utilize harmful substances) and raw-material selection. There are various eco-labelling schemes as well as fair-trade labels each indicating different aspects of sustainability. Two examples of eco-labelling schemes for textiles are presented below.

There are three Oeko-Tex standards: 100, 1000 and 100 plus (Mowbray et al. 2010).

Oeko-Tex 100 was established in 1992 and aims to inform the consumer about the environmental performance of textiles. It is a testing and certification system for textile end products, including raw and intermediate materials at all stages of production. Tests include mainly human toxicological parameters regarding chemical residues (e.g. pesticides). The standard sets more strict requirements than existing chemical regulations and adopts a precautionary approach to safeguard health.

Oeko-Tex 1000 and 100 plus are extensions of Oeko-Tex 100. The Oeko-Tex 1000 standard covers testing, auditing and certification of environmentally friendly production sites throughout the textile value and supply chain (manufacturing processes and social standards). The 100 plus is a product label providing textile and clothing manufacturers with the opportunity to communicate the environmental and human-toxicological performance of their products to consumers.

The Global Organic Textile Standard (GOTS)[15] defines requirements to ensure the organic status of textiles. It incorporates various stages of the textile life cycle including harvesting of

[15] http://www.global-standard.org/the-standard.html

the raw materials, environmentally and socially responsible manufacturing and labelling. It aims to provide a credible assurance to the end consumer. Processors and manufacturers are able to supply their organic fabrics and garments with one certification accepted in all major markets. Basic features of GOTS are as follows:

- requires the use of certified organic fibres.
- provides both demanding environmental and social criteria.
- the criteria are applicable to all processing stages,
- a certification must base on independent on-site inspections.

Conformity with the standard is to be verified by an independent organization following ISO / IEC Guide on Product Certification and the International Requirements for Organic Certification Bodies (IROCB).

The design for recyclability has not been considered a priority in the clothing sector since old textiles are not considered special waste (in contrast to e-waste). The collection and recycling of old textiles from post-consumer waste streams is still lagging behind its potentials. Recently however, there are various scientific and commercial initiatives that develop industry scale recycling of old clothing (e.g. the EU eco-innovation projects Textiles4Textiles and IDENTITEX)

1.5.2. Life cycle assessment as a decision support instrument in eco-design

The holistic assessment of the environmental impacts of products from a life-cycle perspective is a crucial precondition of success for eco-design. The UNEP points out that there is a *“need to help decision-makers identify priorities”* to make environmentally conscious choices in favour the more sustainable design option (UNEP, 2010). The most advanced decision-support method for eco-design is Life Cycle Assessments (LCA) as it “*provides this help from a life-cycle perspective in a systematic and scientific way*” (ibid). The LCA method, specified in the international standard ISO 14040, features a high degree of scientific rigour. The standardised LCA method offers a universally applicable assessment approach that yields transparent and credible results. A review of the LCA application areas and the advantages for the support of eco-design is provided in section 6.1.

However, the LCA methodology is optimised as an ex-post assessment framework. It takes into account only such environmental impacts of products that have a high likelihood of occurrence. Moreover, the method is dependent on quantifiable data about product properties, functions, and use. Such information is hard to establish before actual reference products come into existence. Therefore, LCA is usually not applied in the development stage of emerging technologies (such as smart textiles). This leaves the designers of novel high-tech products in a state ignorance regarding the possible environmental impacts of their design decisions. In common business practice, the development of new technology generations happens often without optimisation of their environmental properties. It is noticeable that designers, especially those working in small companies, do hardly apply LCA in practice (Stevels et al. 1999; Prendeville, 2011).

That shortfall in practical implementation of LCA appears to be a persistent issue although much methodological progress has been made since the early days of LCA. The scientifically robust LCA necessitates rather sophisticated computer software (Gabi, Simapro, Umberto) and access to expensive life cycle inventory (LCI) databases (such as Ecoinvent) (Frischknecht et al. 2005). These LCA tools are often unavailable to product designers, especially in small companies, due to the relatively high investment costs for software and databases. The early stage of technological innovations poses additional challenges for LCA. The 'upstream' or 'background' life cycle inventory data of emerging technologies have not yet been analysed and verified so that these data are missing out from LCI-databases. There is also a lack of experiences with the use phase of future products and the modalities of recycling and waste disposal in future. The anticipation of life-cycle wide environmental aspects of emerging products is thus hardly feasible in the classical way of undertaking LCA. As a consequence, the environmental impacts of emerging technologies often have not been assessed when they first enter the market. As usual, LCA is being applied only ex-post when products need to be re-designed so as to improve their environmental performance. But, for reasons explained in section 1.4, the re-design of commoditised technologies leaves little freedom of design. It is then usually too late improving the environmental properties fundamentally.

This brings up the need to improve the prevailing status quo in environmental decision-making during the technology innovation process. There is an interest for an environmentally conscious decision support approach that can be easily applied in the design stage of emerging product generations, prior to their market proliferation. The specific circumstances (i.e. uncertainty about product properties and functions, absence of inventory data on new materials and processes, lack of resources, skills, and incentives) require the LCA approach to be rethought and to be adapted is a way that makes it a useful decision support instrument for the developers of an emerging technology, such as smart textiles. Hence, the scientific challenge of this PhD research is to explore how LCA could be applied as an instrument for ex ante decision support at the early stage of technology innovations.

1.6. Framework and methods of research

1.6.1. Objectives and research question

This PhD research aims to facilitate a more sustainable development of emerging technologies. The purpose of this dissertation is to support environmentally conscious design (eco-design) as an anticipatory strategy for the prevention of adverse environmental impacts of future product generations. The central research question of this dissertation is:

"How can environmental risks of emerging technologies be prevented at an early stage of the innovation process?"

The research uses a technology assessment approach to prepare intelligence about the prospective environmental risks of a nascent generation of high-tech products: smart textiles.

Stemming from the central research question, three sub-questions are derived for the research on the case of smart textiles:

Q1: What are the environmentally relevant properties of smart textiles and what environmental risks can be expected to emerge during their product life cycle?

Q2: What is the status quo of implementation of environmental risk assessment and risk mitigation in the innovation sector of smart textiles?

Q3: How can eco-design be applied at the early stage of smart textile technological development to prevent environmental risks?

To answer these research questions, a forward-looking understanding of life-cycle wide environmental implications of smart textiles is established as a base for design decisions leading to future mass products. The ongoing innovation process is analysed to identify drivers and barriers for sustainable innovations. Moreover, the research takes a closer look at the technology developers' scope of action to mitigate environmental risks in a preventative manner. The outcome of the research will be a set of heuristics, which can be used by smart textile designers during the early stage of the product innovation process.

1.6.2. Methodological framework of the research

Technology assessment (TA) was the general methodological framework of this research. A definition of technology assessment has been established by the TAMI project: "*Technology assessment (TA) is a scientific, interactive and communicative process which aims to contribute to the formation of public and political opinion on societal aspects of science and technology.*" (Europäische Akademie GmbH, 2004. p.4)

TA is a scientific instrument for the investigation of the intended impacts and unintended side effects of technologies. The methodological framework is often applied in the ex ante assessment of technologies in the context of their prospective adoption into societal and economic circumstances. TA generates forward-looking knowledge about possible future effects of a technology as a means of scientific policy advice (Grunwald, 2007). As such, TA takes not only a natural science perspective on the effects of a technology but also due consideration of societal (and environmental) implications. A detailed review of the TA methodological framework has been provided in a preparatory report to this dissertation (Köhler, 2008).

The reference system of TA determined the choice of case study subjects and experiments undertaken in the course of this research. Thereby, the focus of the research was on the identification of possible environmental risks of smart textiles and the options to prevent such risks during the innovation process. For this reason, the research was guided by the procedure applied in risk management (Figure 1-7) as defined by the international standard ISO 31000.

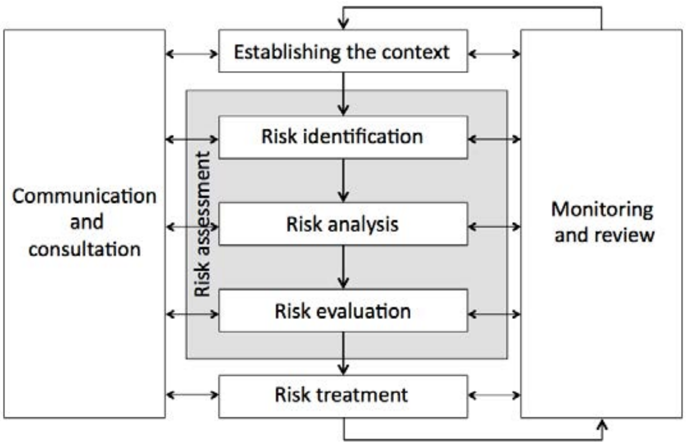


Figure 1-7: The risk management process according to ISO 31000 Source: (ISO 31000:2009)

An interactive research approach was chosen in an endeavour to establish a bi-directional risk communication and consultation with the stakeholders. With respect to fast moving innovation processes it was attempted to publish the research findings in a timely manner. The means of communication included peer-reviewed academic journals, conference presentations, workshops and focus-group discussions as well as online dissemination of research findings. Thus, the dissertation is build upon a paper-based approach where each of the chapters 2 to 8 consists of papers and reports that were published or submitted for publication during the implementation phase of research.

1.6.3. Research methods

Validity and reliability of the research

The research was undertaken within a four-years period from March 2009 to February 2013 and carried out by the author of this dissertation. Details of the methodological approaches of each part of the study are explained in the respective chapters. The general mode of research was qualitative exploratory research (Creswell, 2002). Exploratory research was undertaken to systematically investigate the state of knowledge on risk-relevant aspects and to collect available data on a specified subject of study. The findings of exploratory research are not meant to support conclusions beyond the context of the research (Babbie, 2010). The research context included SMEs in the smart textiles sector in the European context.

The choice of a qualitative approach was justified by the prevailing uncertainty regarding the environmental impacts of smart textiles. At the early stage of their developmental process, data are unavailable for most aspects that are relevant for the quantitative analysis of risk (e.g. empirical data on the likelihood of environmental impacts). Another reason for the lack of robust quantitative data is the small sample size of study subjects in the smart textile sector (only few specimens of smart textiles were available; the number of actors in the innovation system is limited). Under the circumstances, the ex ante assessment of potential risks must rely on the best available information (ISO, 2009).

Credibility of the research

All research activities were carried out in accordance to the core values of the Delft University of Technology (TU Delft)[16]. During the research period cooperation with researchers at TU Delft and other organisations/companies was established. The author acted independently from third party interests and the results of the research were not subject to any personal conflicts of interest. Parts of the research leading to these results received funding from the European Union Seventh Framework Programme (FP7/2007- 2013) under grant agreement N° 265096 through the participation in the “LCA-to-go” project. These parts of the PhD research were guided by the goals and objectives of “LCA-to-go” laid down in the description of work. The research implementation was subject to the provisions of the consortium agreement with other project participants. Besides that, a number of third parties were engaged with, for instance in form of jointly supervised graduation projects at MSc level. The research cooperation with companies was not subject to non-disclosure agreements. This retained a academic freedom of research but it limited the accesses to primary data from these actors.

1.7. Structure and outline of this dissertation

The dissertation consists of a compilation of papers that have been published in peer-reviewed international journals as well as manuscripts that are in the peer-review process[17]. Chapter 6 is based on published project reports and a conference paper. Each chapter contributes with a

[16] Code of Ethics TU Delft

[17] Certain information and references are repeated in different chapters due to its paper-based approach of this dissertation.

particular perspective to the following line of thought: How the framework of eco-design can support the anticipatory mitigation of environmental risks at the early stage of technological innovation in the case of smart textiles. Figure 1-8 depicts the coherence of the chapters that are summarised below.

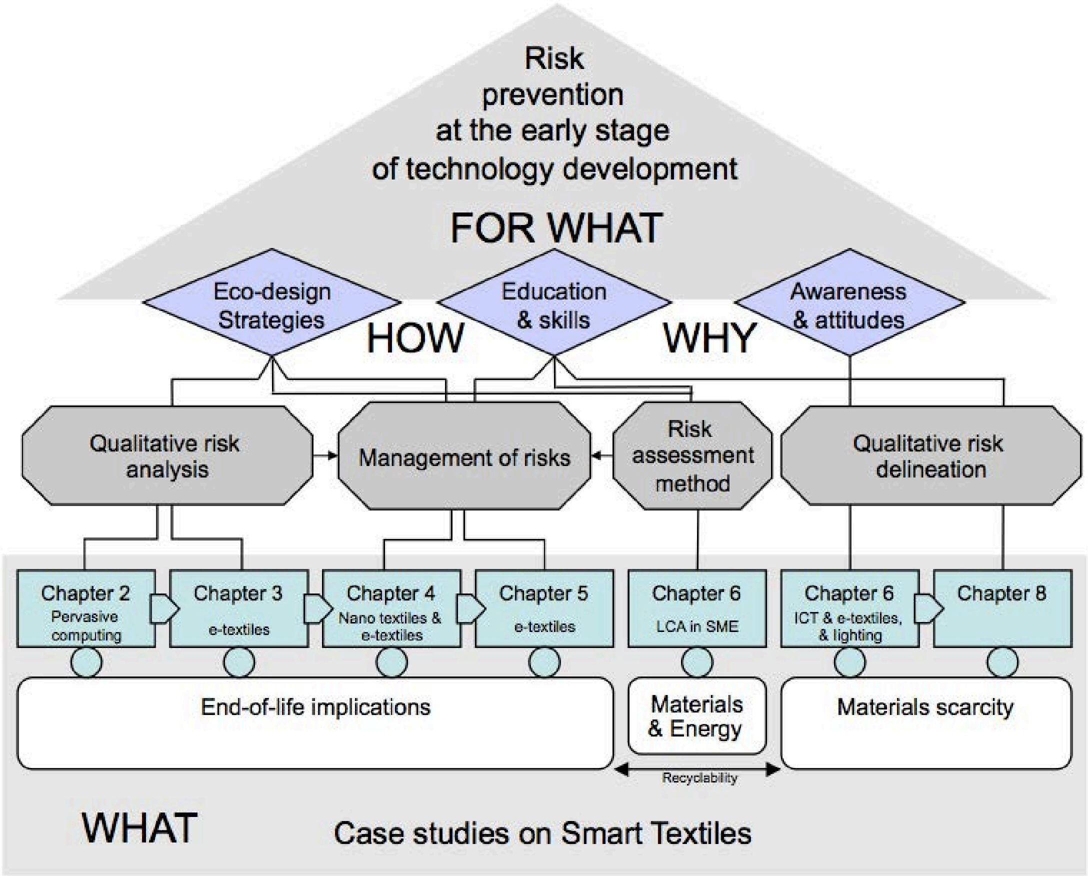


Figure 1-8: Coherence of the chapters in this dissertation

Table 1-1: Allocation of the research questions to the chapters.

R1:	What are the environmental relevant properties and risks?	2; 3.2-4; 4.4; 5.3; 6.6; 7.2; 7.7;
R2:	What is currently being done in the innovation process?	4.5.2; 5.4; 6.5; 8.3;
R3:	What methods and measures could be taken?	3.5; 4.6; 5.5; 6.6; 6.7-8; 7.4.-6; 8.4-5;

The first two chapters feature the ex ante assessment of possible end-of-life risks of smart technologies. Chapter 2 investigates the first, second and third order impacts of pervasive computing on environmental aspects. A broad assessment of computerised everyday objects leads to the conclusion that the emerging technology cannot be expected to unfold without causing environmental risks, e.g. end-of-life impacts. Chapter 3 follows up at this point and takes a more detailed look into prospective recycling and disposal issues of electronic textiles. The product properties are evaluated against the state of the art of recycling schemes. A scenario analysis attempts to provide a grasp of the possible order of magnitude of the emerging waste problems. Chapter 4 reviews the theoretical reasons of risk management under condition of uncertainty. Two case studies on emerging technologies (nano-textiles and smart textiles) show that environmental and safety risks are often intangible at the early stage of innovations. Risk preventative technology development should therefore include life cycle thinking, eco-design, and governance of innovation. These risk prevention strategies are developed further in Chapter 5. E-textiles serve again as a case study to elaborate how eco-design approaches could be implemented at the early stage of technology development. The chapter concludes that forming awareness and education are risk prevention strategies, next to eco-design measures.

Chapter 6 shifts the perspective away from end-of-life aspects to life cycle assessment (LCA) as it focuses on the decision support needs of smart textile SMEs. At first, the LCA needs of small companies are investigated, then, a simplified LCA approach for smart textiles is outlined. LCA is a decision support instrument for the identification of environmental risks of products. It provides product designers with information on environmental improvement potentials.

The chapters 7 and 8 pick up a particular risk associated with emerging technologies: material scarcity. This phenomenon bears the potential to inhibit technological innovations if the supply of critical elements becomes tight. The articles delineate this risk and look into the action potentials of product developers to prevent further depletion of critical resources. It is argued that existing eco-design approaches are insufficient to address the phenomenon. The conclusion in chapter 9 provides a synopsis of designerly risk prevention strategies and provide answers to the research question.

References

See list of references at the end of chapter 9.

CHAPTER 2

Expected Environmental Impacts of Pervasive Computing

Published in: Human and Ecological Risk Assessment 10: 831–852.

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2.1. Introduction

Pervasive Computing is a vision of future applications of Information and Communication Technologies (ICT) in which highly miniaturized, embedded, networked microprocessors equipped with sensors pervade our daily lives: "*A billion people interacting with a million e-businesses through a trillion interconnected intelligent devices*" (Gerstner 2000)[18]. Pervasive Computing involves the miniaturization and embedding of microelectronics in non-ICT objects as well as wireless networking. Unlike most of today's ICT products, Pervasive Computing components will be equipped with sensors that will enable them to collect data from their surroundings without the user's active intervention.

Present ICT has already become a serious threat to the environment. Three types of environmental risks or hazards caused by ICT products and infrastructures can be discerned: global resource depletion, energy use, and the emission of toxic substances over the lifecycle (production, use, disposal).

The requirements of semiconductor production for natural resources are significant due to the highly organized structure of microelectronics. For example, the total resource consumption during the lifecycle of a single 32 MB DRAM memory chip of approximately 2 grams amounts to: 1.6 kg of fossil fuels, 27 g of various chemicals, 700 g of elemental gases, and 32 kg of freshwater. Furthermore, 41 MJ of energy per chip is needed in the production chain of silicon wafers (Williams et al. 2002). For a complete personal computer including CRT-monitor, the input of abiotic raw materials is up to 1500 kg (Türk 2003).

Since ICT has become a mass product, its share in electricity consumption in national economy scales has continuously increased during the past decades. In Germany the ICT-related consumption of electric energy has risen up to 38 TWh in 2001, which is 7.1% of total electricity consumption (Geiger and Wittke 2002). As the generation of electric energy is mainly based on fossil fuels and atomic energy (e.g. 61% and 34%, respectively, of total electric

[18] Update 2013: The forecast, made at the peak of the dot.com hype, has not become reality thus far. However, the high-rising expectations on the future proliferation of networked ICT devices persist. The telecommunication industry expects that, in 2020, over 50 billion devices will be interconnected (Internet of things) (Weiss, 2012).

energy in Germany), the emissions of climate relevant carbon dioxide and radioactive waste are the most important environmental impacts of the ICT use phase.

The rapidly growing amount of ICT equipment is causing increasing problems in the disposal (end-of-life) phase of the electronic waste. The annual amount of scrap from electronic equipment is estimated to be 68,000 metric tons in Switzerland and 2.1 metric megatons in the United States (EMPA 2004a; USEPA 2002). Recycling or disposal of computers and tele-communication hardware is problematical, because electrical and electronic equipment includes a multitude of components causing human and ecological risks, such as heavy metals and halogenated organic compounds. In case of inadequate disposal or recycling, the emission of toxic substances from electronic waste can pollute water, soil, and air, and harm human health. The technically complex problem of electronic waste disposal is not taken care of equally well in all parts of the world.

Will upcoming generations of ICT strengthen or weaken these environmental impacts? Initial technology assessment studies on the impact of ICT on environmental sustainability indicate that not only established ICT, but also Pervasive Computing applications, will have a significant impact on environmental sustainability in the European Union (Erdmann and Behrendt 2003; Goodman and Alakeson 2003; Hilty et al. 2004). A study commissioned by the Swiss Centre for Technology Assessment (TA-Swiss), pointed out potential opportunities and risks of Pervasive Computing in the context of the Precautionary Principle (Hilty et al. 2003). Based on the results of this study, we show here the expected effects of Pervasive Computing on the environment.

2.2. Approach of the Study

The assessment of the effects of a future technology such as Pervasive Computing has to deal with two types of uncertainty: First, it is an open question as to how Pervasive Computing will develop in the various fields of application (path uncertainty), and second, the knowledge base for the lifecycle assessment (LCA) of electronic products is incomplete (data uncertainty).

Pervasive Computing comprises a broad and dynamic spectrum of technologies and applications. Therefore a narrow definition of system boundaries, as required for practical reasons to conduct a lifecycle analysis (LCA), is inadequate to reflect the character of Pervasive Computing. In general the LCA methodology (ISO 14040) (ISO 1997) is difficult to apply to microelectronic products. For example, an inventory analysis of microchip production has to deal with more than 400 processes, vertical ranges of manufacture, and dynamically changing global supply chains (Nissen 2001).

The data uncertainty encountered in the "LCA for ICT" field can only be dealt with by taking into account the few existing LCA studies for ICT while considering the uncertainty of their results. Only simplified LCAs have been conducted so far in the ICT field (e.g., Aebischer et al. 2000; Geibler et al. 2003; Goodman and Alakeson 2003; Stutz and Tobler 2000; Williams et al. 2002; ZVEI 2000). Because of the high overall uncertainty of the results, they are only used to identify priority areas for precautionary measures, not to make a quantitative forecast of environmental impacts.

Experience with LCAs of ICT products and services has shown that the uncertainties of user behaviour—which is a factor relevant to assessing the use phase— are usually higher than the uncertainties of knowledge about production processes (Reichart and Hischier 2001). In order to cope with path uncertainty, scenario analysis was used to cover a spectrum of the possible paths of development. Three possible paths of future development were taken into account and described in scenarios. We defined three scenarios for Pervasive Computing with a time horizon of 10 years (until 2012):

- Cautious scenario: Pervasive Computing will only develop in areas that are already pervaded by networked microprocessors (such as the automotive sector).
- Average scenario: Applications fields and their markets develop according to the trends that can be observed today, without being pushed or counteracted significantly.
- High-tech scenario: Pervasive Computing will be ubiquitous (everywhere, any-time computing in all areas of daily life).

These scenarios differ mainly in the degree of diffusion of Pervasive Computing applications and in the extent of connectivity. The application areas chosen for applying the scenarios were "housing," "traffic," "work," and "health," of which the most dynamic one was traffic. In addition, three cross-sectional technologies—future digital media, wearable computers, and smart labels—were investigated, of which smart labels are expected to become the first type of application to form part of our daily life. The reader is referred here to the original study for a detailed description of the scenarios and application areas (Hilty et al. 2003).

All defined scenarios and application areas were reviewed by an external interdisciplinary expert board set up by the client of the study (TA-Swiss). Based on the scenarios defined, we made rough quantitative assessments (case studies) for selected application areas in order to extrapolate trends into the future. Thirty-nine researchers and other experts from industry, NGOs, and public authorities were interviewed after being briefed about the preliminary findings. They were first asked to help identify potential applications of Pervasive Computing likely to be in place by 2012. Second, their appraisals of the consequences of technological developments on selected environmental topics were gathered in formal expert interview situations or discussed in expert workshops. Repeated consultations of the selected experts both from science and from politics contributed to the validation of the results and to the identification of priority areas for precautionary action.

The ascertained effects of Pervasive Computing on the environment were structured in a conceptual framework that distinguished among three levels of environmental impact of ICT (see, e.g., EITO 2002; Fichter 2001; Schauer 2003; Türk et al. 2002):

1. First-order effects: Includes all environmental impacts resulting from ICT hardware during the product lifecycle, covering production, use, and disposal.
2. Second-order effects: The use of ICT causes effects to other processes such as traffic or industrial production and influences their environmental impacts indirectly.

3. Third-order effects: Owing to the assumed widespread use of ICT in daily life, economic structures and lifestyles can change, indirectly affecting the expression of first- and second-order effects.

In the following sections we shall discuss our specific findings according to this scheme. Because the task was to identify potential risks of Pervasive Computing and to suggest precautionary measures for Switzerland, the case studies reported in the following sections refer to the Swiss context.

2.3. Assessment of the environmental effects of Pervasive Computing

2.3.1. First-Order Effects

The first-order environmental effects of Pervasive Computing include all environmental impacts caused by the physical existence of the technology over the entire lifecycle, covering production, distribution, use, and end-of-life phases. Key indicators for the environmental impacts are the lifecycle-wide energy and raw material consumption and the output of waste heat, solid waste, and the emission of substances into air, water, and soil. Basically, first-order environmental effects originate from the mass and energy flows needed for making Pervasive Computing possible. In the following text, two first-order aspects were given special attention, as they are presently widely discussed issues involving ICT.

2.3.1.1. Electricity consumption of pervasive computing

Electricity consumption is linked directly to environmental impacts by the supply infrastructure, for example, emissions from fossil fuel combustion or the radioactive waste problem. The ICT sector currently contributes 1840 GWh/a (3.59%) to Swiss electricity consumption (Brunner et al. 2001). According to Arthur D. Little (2001), electricity consumption of all commercial ICT will grow from 3% in 2001 to a maximum of 4% in 2010, or, on the other hand, might decrease to 2% if energy-efficient practices are pushed through. For Germany the share of electricity consumption related to ICT is expected to rise from 1% in 2000 to about 6% in 2010. If energy efficiency potentials were utilized, the share would stay around 1–3% (Langrock et al. 2001). Although the figures differ, those studies emphasize current ICT as a considerable factor for future electricity consumption.

Regarding power supply, the following categories of ICT can be distinguished from one another and classified by electricity demand:

- ICT devices connected to the mains[19], such as today’s stationary PCs. According to the vision of Pervasive Computing, these ICT devices will become less important in the future and thus represent a minor, energy-relevant factor.
- ICT devices powered through a mains adaptor and rechargeable batteries in a way similar to that for today’s notebooks, PDAs, and mobile phones. As these kinds of devices are becoming more ubiquitous, the energy efficiency of mains adaptors and power manage-

[19] ‘Mains’ refers to electrical power supplied by an electricity generating plant.

ment technology will be important factors in the future. Energetically more efficient power supply technologies such as low temperature fuel cells are expected to enter the market in the coming years. As a consequence electricity demand per unit will decrease as the demand for alternative fuels such as methanol or propane increases.

- Networked household appliances with embedded ICT ("smart home" concept), which draw energy from the mains, require additional power. Always-on devices in particular and devices in stand-by mode will cause significant total electricity demand.
- Semi-stationary infrastructure for wireless short-range communication. It must be assumed that a widespread application of W-LAN or radio frequency identification (RFID) readers will result in a growing stock of always-on radio transmitters whose transmitting power of up to 2 watts must be powered by mains adaptors. As a consequence, additional electricity consumption is to be expected.
- Stationary backbone infrastructures for the Internet and mobile phone networks. A more intensive use of network infrastructures is probable as automatically generated data transfer will definitely grow due to Pervasive Computing (Langheinrich and Mattern 2003). Extended server and network operation will result in additional electricity demand.
- Mobile and, in particular, wearable devices that will be smaller, lighter, and more common than today. As changing or recharging batteries repeatedly seems to be unacceptable to users, consumer acceptance and functional reasons will make new concepts of energy supply necessary. For this reason Pervasive Computing will provide additional incentives for the development of alternative energy sources, for example, photovoltaics or piezo-elements as well as for minimizing the energy consumption of devices.
- Components with passive energy supply (e.g., RFID transponders). Such components with negligible energy demand do not contribute to electricity consumption itself, but in the case of passive RFID technology transponders must be powered by local inductive supply fields, the efficiency factor of which is low.

Pervasive Computing will evolve on the basis of existing ICT and will therefore spread over most of these categories. Which power supply technologies will be developed will depend on the purpose of the particular application. For mobile, location-independent use, there are strong incentives for producers to minimize power consumption or to utilize alternative energy sources, whereas stationary devices may develop in a less energy-efficient manner than they have thus far. How Pervasive Computing will change the patterns of electricity use is uncertain, as technical parameters and application patterns cannot be forecast.

The risk of increasing energy consumption is illustrated for two case studies, home networks subsumed under the term "smart home" and mobile network infrastructure for mobile phone technology.

Electricity Consumption in Highly Networked Private Households.

The term “smart home” refers to the concept of a private home, equipped with many Pervasive Computing functions (Futurelife 2004; Smarthome 2004). To analyze the electricity consumption caused by smart homes, we take as a starting point the results of a study done by Aebischer and Huser (2000) and apply them to our scenarios. Electricity consumption resulting from networking in private households will reach an annual growth rate of 1.3% and will therefore be the most important factor of growing electricity consumption in the domestic sector in industrialized countries. We have assumed that technological efficiency gains will be compensated for by an increased demand for services.

The following considerations are a conservative assessment of the impact of Pervasive Computing on household electricity consumption. The results for single household types have been extrapolated to the macro-level, considering one- and multi-family houses, diffusion rates, saturation rates and diffusion times. Additional electricity demand can be calculated for the three scenarios, given the assumption that electricity consumption will be mainly caused by hardware used in a supplementary fashion, and a shift in use patterns.

The data in Table 2-1 show significant additional electricity consumption for all scenarios. In the average scenario, the additional demand is almost equivalent to the electricity consumption of all computer and network installations in Switzerland today (Brunner et al. 2001).

Table 2-1: Additional electricity consumption for networking in 4 million private households in Switzerland (Hilty et al. 2003).

	Cautious scenario	**Average scenario**	**High-tech scenario**
Diffusion single- and multi-family houses Additional electricity demand	10% 250 GWh	30% 1000 GWh	90% 3000 GWh

According to Aebischer and Huser (2000) the increase in electricity consumption due to networking in private households overcompensates the potential energy savings by ICT use (e.g., e-commerce and teleworking) by a magnitude of at least one. Similar effects must be expected to result from Pervasive Computing.[20]

If we assume, in compliance with Cremer et al. (2003), that about half of ICT electricity consumption is caused by households and the other half is consumed in offices and infrastructure, and that these sectors will develop similarly, we can extrapolate for both sectors an annual additional electricity consumption of 2000 GWh in the average scenario and 6000

[20] Update 2013: The increasing trend of global household electricity consumption has not been reversed in the last decade (Reinders and Diehl, 2013). Small electrical and electronic devices have contributed in particular to the rapid increase of electricity consumption (IEA, 2009).

GWh in the high-tech scenario. In the latter case, electricity consumption would rise by 7% due to the networking of ICT devices in private households alone.

Electricity Consumption for Mobile Network Infrastructure.

The number of mobile phone subscribers has grown almost exponentially between 1998 and 2000. Now saturation tendencies can be observed. Parallel to the European GSM standard, third generation mobile phone infrastructure (UMTS) is being set up. An increasing number of mobile devices also support ad-hoc network standards, such as Bluetooth, USB, and W-LAN.

Ninety percent of the energy demand of a GSM network is due to stationary infrastructure and 10% is caused by end devices (Schaefer and Weber 2000). The energy consumption of UMTS will depend largely on the number and performance of its Base Transceiver Stations (BTS). BTS for UMTS have a reduced transmitting power compared to BTS for GSM, but the set-up of an enlarged infrastructure and the increasing data transfer caused by the growing stock of Pervasive Computing devices will outweigh the net effect.

As UMTS networks are still under construction, there are potentials for energy-efficient design. One key factor for BTS is having the design of their cooling systems modified for energy efficiency. The energy reduction potential has been estimated at 400 GWh per year for Germany (Stobbe et al. 2004).

Conclusions for electricity consumption

Pervasive Computing will probably increase electricity consumption due to accruing stocks of ICT and network infrastructure and extending power-on periods in an “always on—anywhere and anytime” culture.

Although the power demand of new ICT devices will be lower than the average of the ones currently in stock, the trends toward higher availability (always on, any- time) and higher stocks will counteract that positive potential. A key parameter that will affect electricity consumption in an era of Pervasive Computing will be the energy efficiency of stationary and semi-stationary devices. This is mainly determined by their power supply and cooling systems. There is a risk that inefficient energy schemes will prevail, as no strong incentives for energy-efficient design are given in the international economy. On the other hand, in the case of mobile equipment, functional reasons require high-energy efficiency, so that alternative energy supplies must be developed for them.

The increase in the data transfer of short-range networks caused by Pervasive Computing will require additional capacities in the long-range networks. This will cause an increase in the energy consumption of network server farms, as they need active cooling.

2.3.1.2. Pervasive computing and the risk of cross-contamination

The end-of-life phase of present-day ICT is accompanied by a considerable risk potential for health and the environment, as ICT components contain a multitude of harmful substances such as heavy metals and halogenated organic compounds (Behrendt et al. 1998). In cases of insufficient disposal or recycling practices, the emission of toxic substances from electronic waste can pollute water, soil, and air and harm human health (EMPA 2004b). In addition, the material loss caused by the disposal of these substances instead of recycling them has to be compensated for by extracting additional primary raw materials (e.g., gold and copper mining), which is associated with severe burdens for human health and the environment.

Therefore, an increase in the amount of electronic waste (PCs, entertainment electronics, mobile phones, PDAs, etc.) is to be expected. It will add to the pressure currently on the disposal streams of electronic waste. Miniaturization and embedding in other goods will constitute a considerable part of the Pervasive Computing waste that will be found in residual waste (i.e., not separable using conventional means). However, the mass flows of Pervasive Computing components in municipal solid waste remain relatively small and are not expected to pose a significant problem to incinerators. However, taken together, the loss of valuable raw materials such as copper[21] is considerable and has to be compensated for by extracting correspondingly more primary raw material.

Moreover, Pervasive Computing has an impact on non-electronic waste. For example, electrical household appliances and vehicles will be equipped with printed circuit boards, LCD displays, and power supplies or batteries. Packaging will be “enriched” with small microchips (RFID). The presence of electronic components in objects that were formerly non-electrical will give rise to quality issues in the recycling processes used for those materials.

As the increase of electronic waste in general and the problem of ICT components in vehicles have currently been addressed by the WEEE and RoHS directives of the European Union (European Parliament 2003a,b), we want to emphasize the impact of Pervasive Computing on other waste streams and highlight the risk of cross-contamination. In the following we illustrate this effect, giving two case studies as examples. A case study on “i-wear” will take a closer view of the embedding of ICT in clothes, which may counteract reuse of them. In a second case study, we will discuss the effect of “smart labels” on the recycling of packaging, which may violate the quality requirements common in material recycling processes.

Case Study on the “End of Life Aspects of i-wear”.

The term “i-wear” refers to a concept of wearable computing, which means that garments are equipped with embedded electronic devices (microprocessors, sensors, batteries). Pioneers of

[21] Update 2013: The range of valuable materials being lost in e-waste streams also includes precious metals, such as gold, silver and platinum group elements, as well as critical elements, such as rare earth elements. The recycling rates of these materials from waste are still very low or even zero (see chapters 3 and 7). Castro et al (2007) have shown that the presence of contaminations in recycling materials leads to quality losses of the recycled metals due to the decreasing exergy content.

the concept define i-wear as the combination of mobile multimedia technology with wireless communication and portable computers integrated into clothing. Recent developments have attempted to incorporate electronic systems into the constituent fibbers and fabrics of clothing, or even to incorporate them into a print applied to the garment. I-wear can be powered by integrated dry batteries, and in the future will be powered by fossil fuel cells. Alternative power supplies using body or ambient energy are under development, but rechargeable buffer batteries may be necessary in any case.

Even though the European RoHS directive (European Parliament 2003a) has prohibited the use of certain toxic or environmental risky substances in electronics since August 2004, from the standpoint of the Precautionary Principle, one cannot be sure that no pollutants are present, particularly in imported i-wear. Therefore, embedded electronic devices and batteries will give rise to new end-of-life issues for garments.

What consequence will it have on waste streams if some worn out garments are i-wear? We assessed this by taking Switzerland as an example: Some 18 kg of textiles per capita are sold annually, about 10 kg of which are clothes.

Every year roughly 7 kg per capita are fed directly into municipal solid waste streams and 4.4 kg per capita are collected separately for reuse or recycling (BUWAL 2002). If we assume that a typical consumer buys a 2 kg jacket every 2 years, which is used for an average of 2 years, and take into account a Swiss population of currently 7.3 million, the following waste flows would be expected for the three scenarios (table 2-2). In the cautious scenario annually 0.01 kg of i-wear per capita would be an insignificant amount, taking an annual total of 4.4 kg textiles collected separately per person and year as a reference. However, in the average and high-tech scenarios significant amounts would be achieved.

Used clothes are typically collected for charitable purposes, but we doubt whether second-hand i-wear could be remarketed in this way while retaining its original functionality. A restoration of the functionality is improbable and removal of electronic components from textiles would require a lot of work and might damage the cloth beyond usability. Exporting such garments to developing countries would—quite apart from the question of acceptance — merely shift the end-of-life problems of electronic waste geographically.

Table 2-2: Expected annual waste flows for "i-wear" (Switzerland).

	Cautious scenario	**Average scenario**	**High-tech scenario**
Assumed diffusion	1%	20%	80%
Waste ("i-wear")	73 t / 0.01 kg/cap.	1,500 t / 0.21 kg/cap.	6,000 t / 0.82 kg/cap.
Waste (energy supply)	36,500 batteries	730,000 batteries or solar/fuel cells	3 million batteries, solar/fuel cells or body energy devices
Max. mass of batteries disposed of	1.1 t	25 t	100 t

I-wear in municipal solid waste would be an additional source of pollutants in incinerators and landfills. Consider this: the annual amount of electronic waste in Switzerland is 68,000 t (EMPA 2004a), which corresponds to 9.3 kg per capita annually. I-wear would be responsible for an additional annual 0.82 kg of electronic-like waste per capita in the high-tech scenario.

Batteries found in i-wear would need to be removed and disposed of separately for environmental and safety reasons (fire danger). Dry one-way and rechargeable batteries for electronic equipment contain hazardous substances such as corrosive alkali electrolyte or volatile organic compounds. Also heavy metals, for example, cadmium and nickel, have been found in these components. NiCd rechargeable batteries will disappear from the European market in the near future; however, new types of rechargeable batteries (e .g ., Li-ion or Li-polymer) have to be treated likewise with caution.

In Switzerland currently 2332 t or 67% of the dry batteries sold annually are collected separately and recycled (BUWAL 2002). Assuming an average dry battery weight of 30 g (calculated from UBA 2001) in the average scenario, an additional maximum of 25 t of batteries and in the high-tech scenario an additional maximum of 100 t of batteries would have to be separated from i-wear annually. Compared to the total mass flow of exhausted dry batteries, these amounts are not dramatic, but i-wear is only one segment of Pervasive Computing.

Case Study on "Smart Labels on Packages".

"Smart labels" are thin labels containing a transponder, that is, a microchip used to store data that can be read wirelessly. They use Radio Frequency Identification (RFID) technology.

Smart labels are usually based on flexible substrate materials, such as polyimide or polyester. The antennas are made of thin copper or aluminium layers and most of the commercially available chips use silicon technology. However, there has been progress in metal-free polymer electronics, which allows for the application of electronic circuits using printing technology. Currently it is unclear whether smart labels can be built without metal. The typical smart labels used in retail, transport/logistics, libraries, parcel services, and airlines' baggage traffic have dimensions of 50 × 50 mm and weigh about 0.1 g each (GEMPLUS 2002). The miniaturization of smart labels is limited by the space needed by the antenna for power generation and the frequencies used.

For present applications of smart labels only an estimation of total numbers is possible. From Germany we know that about 200 billion units of sales packaging are sold annually (Reichl 2003). Given a diffusion rate of 100% (complete replacement of barcodes by smart labels) and taking into account an estimated weight of 0.1 g per unit, the total mass of marketed smart labels would contribute to a waste stream of 20,000 t/a within this bottom-up assessment. Taking into account other applications, such as production, postal services, renting, public transport, and so on, might make the total amounts in all scenarios a magnitude higher.

In order to identify the impacts that smart labels may have on recycling, we looked at food packaging recycling as an example. One can distinguish glass, paper and cardboard, plastics, aluminium, and tin foil as the main material types involved. If a high percentage of food packaging is equipped with smart labels, recycling problems might emerge, as smart labels add impurities to otherwise recyclable materials.

For glass-to-glass recycling, paper labels do not have to be removed, as they burn completely in the melting process. If the substrate of a smart label consists of organic materials, they would also burn without any problem, but copper could be introduced into the glass melt. In Germany the standard for impurities in end-of-life glass is max. 5 g/t for non-ferrous metals (Habel 2001). Assuming a smart label weighing 0.1 g on an average glass of 200 g, the share comprised by the smart label would be 500 g/t. If all glass for packaging were equipped with smart labels—as assumed in the high-tech scenario—a conflict with these quality standards is likely to arise. In the Average Scenario the share of smart labels amounts to 50 g/t, a level that would still have to be taken seriously. As a consequence smart labels might have to be removed before glass recycling.

In paper and cardboard recycling, impurities are removed in the pulper. Copper-containing paperclips are a type of impurity that often has to be dealt with. The silicon or polymer substrate of smart labels will be separated in the pulper as well. Therefore the expected amount of smart labels will probably not pose a disadvantage for paper and cardboard recycling. In tin can recycling, compounds and residual adhesives, for example, from paper labels, usually do not cause any problems (IZW 2002). Smart labels based on polymers will burn in the blast furnace, silicon substrate would enter the slag. On the other hand the input of copper into steel is not desired, but the accumulation of copper in steel is a problem that is not specific for Pervasive Computing. Taking the high materials flows of shredder scrap and related copper loads into account, the impact of smart labels is negligible.

In aluminium recycling impurities such as paper labels are burned in the smelting process. Copper is especially critical to aluminium recycling. The amounts of other heavy metals and silicon also have to be limited, varying from alloy to alloy. Allowed impurities are on magnitudes between 0.001 to 5 percent by weight. Smart labels based on silicon might cause conflicts with quality standards. An aluminium package of 50 g with a “smart label” weighing 0.1 g has an impurity content of 0.2-percent by weight. The copper content may reduce the market prices of smart-labelled aluminium scrap, which might thwart recycling solutions for aluminium beverage cans.

Thermoplastics, such as PET bottles, are smelted at 150–300° C in plastics recycling. Smart labels based on polymers might cause material inconsistencies, whereas silicon substrates are removed by sieves. One problem could be the melting of solders, if, for example, lead is transferred into the plastic and collides with the maximum metal content admitted under the EU packaging directive. In high-tech PET recycling solutions all labels were separated in an automatic presorting process and are therefore not problematic.

The impact of future smart labels on recycling processes has to be assessed depending on their composition. Metal-free smart labels based on polymer electronic technology would facilitate recycling of metals, but would influence the quality of recycled plastics.

Conclusions for cross-contamination caused by pervasive computing

Pervasive Computing will cause a high diffusion of a growing number of miniaturized ICT components. Miniaturization and new technologies reduce the content of valuable substances per device. But it is not realistic to assume that miniaturization will cause significant reductions in total material demand on the macro-level (Nissen 2001; Hilty et al. 2003; Behrendt and Erdmann 2004). Growing stocks of hardware may compensate or even over-compensate the effects of miniaturization.

The case studies underpin that the embedding of ICT in previously non-electric objects entails the risk to change waste streams adversely. The large diversity and high distribution of Pervasive Computing entail the risk of cross-contamination. It is likely that pollutants and impurities will cause problems in recycling other materials, for example, the recycling of packaging.

However, a separate collection of single components, such as microchips and batteries for recycling, would require tremendous logistic and technical efforts, entailing the risk of high-energy demand for itself. It has to be checked for which waste fractions a separate treatment makes sense and logistic and separation capacities have to be adjusted or set-up. As a part of large waste flows, no high-level recycling, but only a down cycling seems feasible economically. The small size and ubiquity of Pervasive Computing components will result in a definite loss of valuable materials. Finally it must be clarified under which conditions embedded electronics can be treated together with residual waste.

2.3.2. Second- and Third-Order Effects

The use of ICT has caused structural changes in economics and a decoupling of economic growth from investment in energy and material-intensive sectors (Fichter 2001). Today value is being created increasingly in the immaterial sphere of ideas and information, which have little direct impact on the environment.

ICT use may contribute to relieving environmental impacts. Terms as “dematerialization” and “demobilization” reflect the high expectations being placed on ICT to substitute pure data processing for material and energy intensive processes. Replacing physical goods or processes by virtual services can contribute substantially to increasing resource productivity. This way of saving energetic or material resources (second-order effects) can go far beyond the environmentally harmful processes generated by the production and disposal of ICTs, making it possible, for instance, to avoid traffic by substituting telecommunication for trips. But this potential to relieve environmental impact can only be realized if economic and regulatory frameworks favour the sustainable management of natural resources. Otherwise, a surge in demand can neutralize or even outweigh the possible savings. In almost every case in which ICT use could have made possible an environmental benefit, it turned out that some related or otherwise environmentally harmful activities increased simultaneously. These rebound effects (third-order effects) counteract the environmental benefit expected from dematerialization and are thus to be regarded as a serious risk for the environment (Radermacher 1997).

Considering the uncertainty surrounding the forms and ways in which Pervasive Computing will develop, it is not possible to make a reliable prediction or to present evidence of second-and third-order effects on the environment. Instead it is expected that the conceptual characteristics of Pervasive Computing will intensify or accelerate the same effects that we know from existing ICT. On the other hand, there is no evidence that the use of Pervasive Computing will inevitably entail ecological consequences other than those we know from ICT. Hence, specific environmental effects expected of Pervasive Computing can be evaluated on the basis of the findings made thus far on ICT.

In the description that follows, three environmentally significant cross-sectional aspects are taken as examples, while bearing in mind that these ecological impacts are not determined by Pervasive Computing alone, but also by a concurring series of further technical and socioeconomic factors.

2.3.2.1. Influence on fuel consumption in facilities

Building insulation has become a high-priority action field for climate protection in Switzerland because 42% of Swiss total fossil energy demand is used for heating purposes (BFE 2003). Similar priorities would apply to many industrial countries. Active measuring and control systems supplement energy-efficient heating systems. Computer-assisted facility technologies are equipped with sensors to take inside and outside measurements such as temperature, penetrating sun radiation and wind force. This makes it possible to reduce the loss of heat energy by adapting heating and ventilation to keep operating conditions optimal. Remote control of heat installations per telephone has been part of present-day technology for a while now, and the Internet has more recently been added as an option (Bohn et al. 2003). Although it is not possible to quantify the benefit of ICTs for building insulation, these measures have on the whole been successful. In spite of the increasing number of buildings, it has been possible to avoid an increase in the amount of energy consumed for heating purposes in Switzerland (BFE 2003). The use of ICT in installations for generation of regenerative thermal energy provides additional advantages for climatic protection. The optimal utilization of solar or geothermal energy requires sophisticated control technologies (Koner 1995). Programmable electronic control units with sensor networks can make it more economical, and thus more attractive, to use renewable energy sources for heating (Hastings 2004).

Electronic facility technologies will represent an attractive field of application for Pervasive Computing. Innovative functions of Pervasive Computing such as presence detection and voice or gesture recognition interfaces are predicted to enter the home automation market (Smarthome 2004; Jedamzik 1996). Compared with today's state of the art, such control systems in buildings will integrate considerably more networked components (e .g ., sensors, actuators), functions (e .g ., remote control, thermal control for individual rooms), and be also connected to external networks. Pervasive Computing components spread throughout a "smart home" will provide both real-time data on usage in individual rooms and, in ideal cases, information on the intentions and living habits of the residents. Such concepts will make possible intelligent heat requirement planning on the basis of prevailing weather forecasts and utilization profiles of the residents (Fleisch et al. 2002). Automated and adaptive energy management will make it possible to make buildings' energy management more efficient (Schratt et al. 2000). Another advantage of using Pervasive Computing consists of avoiding heat losses caused by incorrect manual operation or inadvertence of the users—a great potential of this technology, as user conditioned heat losses also occur in energetically optimized buildings (Spasokukotskiy et al. 2001).

Quantitative estimates of the energy savings that can be obtained with automatic heat control in buildings vary between 15 and 35% of today's total heating energy use. That yields a net benefit for the purposes of energy saving, although to a lesser extent if the performance factor of electricity generation is taken into account (Cremer et al. 2003).

However, it would be wrong to think that Pervasive Computing automatically results in the saving of energy. The opportunities have to be seen in opposition to a number of risks due, on the one hand, to the functionality of technology and, on the other hand, to human interaction with technology. From the standpoint of energy policy, the use of Pervasive Computing for the energetic optimization of buildings must be considered critically. Energy-efficient architecture is also feasible and economically attractive without using "smart" electronics (Jakob et al. 2002; see also Aebischer and Huser 2000). If one overestimates the advantages of electronic control systems, one runs the risk of neglecting the fact that passive heat protection concepts have proven to be energy saving and economical. On new buildings, they clearly represent the better alternative, while Pervasive Computing assisted control systems have to be seen, at best, as a useful supplement. Systematically applied to existing buildings, they have the potential to save 3–6% of total energy consumption under West-European conditions (Arnfalk et al. 2004).

Quite particularly the increased complexity of electronic control systems incorporating Pervasive Computing makes high demands on thorough planning, calibration, and maintenance. In cases of inexpert or omitted planning and practice, there is a high probability that air conditioning will be insufficiently optimized or that Pervasive Computing–assisted systems will malfunction. As a consequence of the complex interaction of their various hardware and software components, it will be harder to detect energetically unfavourable operating situations with these systems, or to even remedy obvious malfunctions. Should a large portion of systems develop such technical problems, they might in total cause a considerable loss of energy.

Whether these technical problems will cause an increase in total energy consumption depends mainly on the area's energy policy. If there are no external incentives for optimizing energy efficiency, energy losses will be accepted, as usual, for reasons such as comfort. It will depend mainly on whether energy efficiency is financially profitable. As a personalized accounting system for heat, warm water, and power (micro-billing), the use of Pervasive Computing offers great potential for energy saving, especially in the rental flat sector. An equitable "pay as you consume" breakdown of expenses is known to motivate individual users to save energy (Diekmann 1994). If the use of Pervasive Computing makes it possible to influence consumers' behaviour by improving the link between cost and consumption, this indirect way of saving fossil fuel could contribute noticeably to protection of the global climate.

2.3.2.2. Influence on the traffic system

Transport processes rank as some of the ecologically most relevant economic processes that exist: goods and passenger traffic add to the pollution of the environment due to the surface sealing needed for roads, the consumption of resources (fuels), and the emissions they cause (greenhouse gases, air pollutants, noise). However, the different means of transportation differ considerably with regard to their performance per environmental load unit. As compared with the car, the railway needs on average a third of the primary energy per passenger kilometre, and compared with short-haul flights, only a fourth (Westenberger 2004). Just how environmentally relevant a given means of transportation is does not depend, in the first place, on how much ICT equipment it has. Nonetheless ICTs do have the potential to influence the environmental efficiency of passenger and goods transport. Within the mobility sector, selection of the means of transportation can be influenced by ICT, and for goods environmental efficiency can be improved by avoiding unnecessary trips. The essential environmental effects of present-day and future ICTs within the mobility sector can be listed as follows and illustrated with examples:

- Improvement of the eco-efficiency of engines and exhaust gas filters or catalytic converters by using electronic control systems in the vehicle.
- Optimization of mobility by better planning itineraries and better utilizing vehicles and infrastructure.
- Substitution of telecommunication for traffic processes.
- Induction of additional traffic processes over longer distances as a consequence of telecommunication.

2.3.2.3. Improvement of Technical Eco-Efficiency.

Electronics has been the main basis for progress in prime mover technologies in recent years. The use of electronic control systems has made train control energetically more efficient (UIC 2003; Ahman 2001). Modern high-speed trains such as the German ICE3 consume merely the equivalent of 2 litres of gasoline per passenger on 100 km when carrying an average load (Köser 2003). The trend of using ICTs has grown even more intensively in cars: nowadays a top-of-the-line-model car is equipped with more than 30 microprocessors (Burkhardt et al. 2001). On-board computers make possible a more uniform operation of engines, thus lessening considerably the frequency of starting and braking. Such “motronic” systems improve engine operating performance and simultaneously make it possible to save fuel and reduce the amount of pollutants emitted with the exhaust gas. Due to the increased overall number of cars, however, the improvement of technical efficiency has not been enough to reduce the total consumption of fuel (BFE 2003).

Optimization of Mobility Services.

Pervasive Computing can make traffic-related information available faster and just when it is needed most. That leads simultaneously to increased efficiency of individual mobility and of

the whole traffic system. In addition, navigation computers can plot one's optimal itinerary, avoiding unnecessary detours and relieving the impact on the environment (Hartmann et al. 2003). In the high-tech scenario developed in the study by Hilty et al. (2003), traffic information (time-tables, etc.) is available for pedestrians as well as for motorists by means of wearable computers offering individual mobility logistics independent of their location. Travellers may ask for logistical answers to their mobility requirements at any time by means of a Personal Travel Assistant (PTA). As the need to plan is one of the handicaps of public transport in opposition to taking the car, such individual logistic assistance would indeed contribute to the attractiveness of busses and railways. But also in this case, rebound effects must be expected to set in, just as rebound effects have compensated for past ICT optimization potentials in passenger traffic. In spite of the attractive public transportation available in Switzerland, the upward trend in motorized individual traffic is continuing (Arendt and Achermann 2002). We are therefore forced to conclude that the additional optimization potential offered by Pervasive Computing will not noticeably reduce the environmental impact of traffic on a macro level, as long as the business and regulatory environment of low energy costs and
externalization of environmental costs remains unchanged.

Substitution of Telecommunications for Traffic Processes.

Progress in telecommunications has been expected to make trips for persons superfluous for some time now, and thus to help save time, energy, and emissions. Trips are often intended to make contacts and exchange information. The same can be achieved with information technology without requiring any physical movement of the communicating partners. The lifecycle assessment (LCA) of an international conference in Zurich illustrates clearly this potential for substituting telecommunications for traffic processes: The effective environmental impact of the trips of 500 international participants (with 35% flights) was calculated with 4207 Ecoindicator Points (EIP). In the hypothetic case of a video conference, feasible with today's ICTs, such a meeting would have merely caused 10 EIP. Although such a totally dematerialized scenario does not have much relevance in practice, the more realistic scenario of a virtually connected conference at three conference sites (Zurich/Dallas/Tokyo) would still represent an ecological gain of about 50% as compared with a single central conference venue (Hischier and Hilty 2002).

Induction of Traffic by Telecommunication.

There are nevertheless serious doubts about whether such examples represent ways to really take impact off the environment by using telecommunications. Virtual communication cannot totally be substituted for personal contact (Rangosch 2000). On the contrary, the number of business contacts and the distances between them have increased sharply with the spread of telecommunications. As a consequence, both business travel and virtual communication have definitely increased (Rangosch 1997; Arnfalk 2002).

Such rebound effects must also be expected to limit progress as virtual communication by Pervasive Computing becomes more attractive. Similar impacts are also certain to arise with an increase in leisure time. The popularization of the Internet has also boosted considerably the number of long distance contacts in business and private life (in the form of Internet chatting, for instance). Over three-fourths of these contacts made virtually entail repeated personal meetings and consequently involve travel by the participants (Zoche et al. 2002).

In addition to stationary applications, wearable computers and other mobile Pervasive Computing components (Web pads, e-paper) will make possible virtual communication and consumption of information and entertainment media independently of one's location. Present-day Internet users spend an average of 17 hours per week on the Internet (Hahn et al. 2000) and thus stay at one place for that time. Stationary online activities have lower negative impacts on the environment than other leisure activities. If Pervasive Computing makes it possible to use media services over a mobile connection as well, the user will no longer be bound to the location by a wired Internet connection. That will contribute to the transfer of at least a part of his/her daily online time to secondary activities on a mobile basis, for example, surfing the Internet while driving a car. Then the frequent leisure traffic we see today (BFS 2002) will grow further. Considering how things have developed thus far, we assess that the risk of an increase in environmental stress from changes in consumer behaviour caused by Pervasive Computing and additional traffic may well overcompensate any potential for mobility optimization.

2.3.2.4. Influence on the service life duration of everyday objects

One environmentally unfavourable property of ICT products is their service life, which averages from 2 to 5 years. That time is short in relation to the amount of resources consumed for ICTs' production. There is a trend toward low-cost electronics, which is leading to even shorter service lives and one-way products (e.g., mobile phones, cameras). As a consequence, the quantities of electronic waste that need to be disposed of are increasing in spite of continuing miniaturization.

The defining characteristic of Pervasive Computing is a miniaturization and embedding of ICT components into everyday objects, so as to make the latter "smart." With regard to the shorter and shorter service lives of ICT, short-lived smart functionality may devaluate the objects in which ICT is embedded much sooner than without. Such "virtually worn" smart objects may be replaced and scrapped long before they become worn out physically. Thus, Pervasive Computing can intensify resource use and the waste problems encountered with goods other than electronic ones. Smart objects will not necessarily be easily identifiable from the outside as containing electronic components (Weiser 1991). At the end of their service lives, the problem may therefore arise that consumers will not identify them as electronic waste, which will make it difficult to collect electronic waste for recycling separately.

Even with a financial motivation like the advanced recycling and disposal fee in Switzerland (BUWAL 2000), it is already obvious that the system presently relying on waste separation by the consumer will not be suitable for Pervasive Computing. Worse still, it must be added that today's collection logistics and most recycling processes are not economical for the recycling of highly miniaturized, single electronic components. The ecologically desirable reintegration of valuable materials and adequate disposal of harmful substances are both important matters of environmental concern in Pervasive Computing. However, it is uncertain whether either of them can be accomplished with the recycling technologies currently available. Therefore it is probable that the share of electronic waste in municipal waste will grow again in the future and may cause problems in waste treatment as well as further the dissipation of precious materials.

2.4. Conclusions

As Pervasive Computing encroaches upon more and more segments of our daily life, leading to an ever-higher dissipation of ICT components, environmental effects occur over the whole lifecycle of the products affected.

As we have shown, a quantification of the net opportunities and risks to the environment do not appear possible due to the highly dynamic character of technological development processes and uncertainties in their application and diffusion. In the range of our scenarios we have identified areas in which Pervasive Computing may collide with environmental goals and thus have to be judged as risks.

While Pervasive Computing is not expected to cause totally new types of impacts on the environment, it is likely to add to the well-known environmental impacts of today's ICT. Consumption of scarce raw materials for the production of electronics and the energy consumption of stationary infrastructure may increase. Furthermore, Pervasive Computing will change electronic waste streams in their amount and quality. If no adequate solution is found for the end-of-life treatment of the electronic waste generated by millions of very small components, precious raw materials will be lost and pollutants will be emitted to the environment. In OECD countries the expected amounts of microelectronics in residual waste are controllable in terms of environmental and health risk. Greater challenges may arise, however, in countries without well-developed systems of waste treatment and recycling. An increasing concentration of electronic waste in household waste streams will aggravate waste-related impacts on environment and health, for example, in the case of illegal landfill or open burning.

On the other hand the intensified use of ICT in the era of Pervasive Computing might result in certain advantages to the environment. Intensified use of information services instead of physical goods can contribute to higher ecological efficiency in economics and consumption. Although Pervasive Computing could bring a potential for dematerialization, it has to be expected that energy and resource savings will not be realizable in every case due to a growth in demand that will overcompensate for the savings (rebound effects).

There is a need for policies that exploit the environmental opportunities of Pervasive Computing while avoiding the risks at an early stage of technological and market development.

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CHAPTER 3

Prospective impacts of electronic textiles on recycling and disposal

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3.1. Introduction

Electronic textiles (e-textiles) consist of clothing or technical textiles with electronic components integrated into them. Clothes provide a wearable platform for electronic devices, making the latter easily portable and more convenient to use in daily life. Interactive clothes with integrated lighting elements, dial pads, mp3 players, and solar cells have already been commercialized (Mecheels et al. 2004). The first-generation of e-textiles has the potential to enter mass markets in the near future (Stork 2008). More advanced e-textiles, with unobtrusively embedded computing devices, are still at an immature development stage. They represent an example of 'pervasive computing' - a technology vision, consisting in the integration of information and communication technology (ICT) into every-day objects (Hilty et al. 2004). Technology developers utilize textiles as a basis for pervasive computing products because many objects of the daily living environment are made of textile materials. E-textiles have a wide range of potential application areas, such as health care, sports and outdoor fashion, work wear, interior textiles, and safety/security products.

E-textile developers currently pursue design concepts that seek a deep and seamless integration of electronics and textiles. Both types of products represent relatively short-lived mass consumer goods. Combining them can intensify the reasons for product obsolescence and may lead to products that have even shorter service lives. That makes e-textiles a subject worthy of scrutiny from the perspective of industrial ecology. If the convergence of textile and electronic products leads to short-lived mass products then it is likely that they will become a source of large waste streams in the future. Moreover, e-textiles will form a new type of waste, namely e-waste contaminated old textiles. Such kind of materials can entail recycling and disposal problems.

Thus far, only a few studies have examined the possible end-of-life impacts of smart every-day objects that contain electronics components. Hilty et al. (2004) assessed the technology vision of pervasive computing and warned of quick premature obsolescence ("*virtual wear-*

out") affecting such products due to short innovation cycles and software incompatibility. The expected consequences are increased resource consumption in production and increased waste generation. Scrapped wearable computers will be difficult to collect and recycle because these tiny devices will be scattered in general household waste streams (Köhler and Erdmann 2004; Kräuchi et al. 2005). Because of their unobtrusiveness, their last owners will find it hard to separate them from residual waste. Thus, numerous small e-waste items can end-up in normal household waste or find their ways into recycling processes where they act as contaminants. This creates a twofold risk: Firstly, recycling processes of other materials may be disturbed by cross-contamination. Secondly, release of toxic substances is possible during unsophisticated disposal processes. Wäger et al. (2005) found that RFID-tags[22] can cause problems in established recycling processes of non-electronic goods.

Experiences with the disposal of contemporary electronic waste (e-waste) give reason to expect severe environmental and social impacts worldwide (Puckett et al. 2005; Hilty 2005; Widmer et al. 2005, Kräuchi et al. 2005, Schluep et al. 2009). The e-waste problem consists in three key factors:

1) Large amounts of obsolete electronic products are arising[23] worldwide.
2) Electronics usually contain problematic substances, which can cause harm to the environment and human health if they are released during disposal.
3) E-waste contains valuable materials, which are difficult to be recovered. E-textiles are expected to fulfil all three factors of the e-waste problem (Köhler 2008).

Future waste problems can be mitigated by environmentally conscious design of e-textiles. Waste prevention by design can be successful at an early stage of technology development. This holds true as long as e-textiles have not pervaded the mass markets. That necessitates e-textile developers to make design decisions under conditions of uncertainty. In this situation "*it is important to understand where we have choices and where we do not*" (Allenby 2009, p181). Allenby also notes (p180), that "*identifying reasonable scenarios for emerging technologies and exploring their implications remains an important priority*" for industrial ecology. To this end, the objective of this article is to examine the prospective end-of-life implications of e-textiles before they become reality. The ex ante assessment of future waste problems serves as a basis for outlining possible sustainable design choices that can be made at the early stage of the e-textiles' innovation process.

The article is organized as follows: First, we outline the most relevant design concepts that influence the direction of innovations in the area of e-textiles. Next, we provide an overview of their materials composition. Finally, we describe and analyze application scenarios of three types of e-textiles as a basis for estimation of future waste streams and evaluate prospective consequences for recycling and disposal of these products.

[22] Radio-frequency identification (RFID) transponder in form of labels
[23] In some countries, the term waste generation is used in lieu of arising.

3.2. Description of E-textiles

Current trends in innovation and market development were examined through review of the technical literature and an expert survey. The survey was conducted among thirty-nine European researchers and enterprises by means of questionnaire-guided interviews. The survey addressed three thematic areas: 1) Design concepts, 2) Estimation of future market perspectives, and 3) Material composition. The expert survey did not aim at empirical robustness; instead it provided a synopsis of current priorities in the research and development process. The interviews were conducted between 2008 and 2010..

3.2.1.Current Innovation Trends

Smart textiles represent an emerging technology that is developed by innovators in both sectors, the electronics and the textile industry. Technophile trendsetters, such as fashion artists and industrial designers, have inspired the innovation process by creating prototypes of textile high-tech products with advanced functionality. In the textile sector, the term “smart” has been used to describe functional textiles with engineered properties. They can contain a wide range of engineered materials and components (Mecheels et al. 2004; Tang and Stylios 2006; Cho et al. 2010). Phase change materials (PCM), for instance, create a cooling effect or store excess heat. Micro- or nano-encapsulated substances can be attached to fabrics and release of these agents (e.g. insecticides, perfumes, drugs) during the use phase in a controlled dosage.

The notion of product-smartness has recently shifted towards more active and “intelligent” functions (Centexbel 2011). Now, smartness is often interpreted as the products’ capability of sensing and responding to external stimuli. Shape memory materials that can adjust the texture of fabrics depending on temperature change are an example. Sophisticated smart textiles show interactive behaviour, such as sensing, signal transmission, and data processing. These functions are established by means of textile integrated electronic components. The term e-textile is specifically used for that technology.

Developers of e-textiles pursue different design strategies, depending on their respective discipline (textiles or electronics). Both disciplines are only beginning to cooperate in the development of dedicated e-textile materials. Apparel designers usually start with traditional clothing and seek to make them smart by integrating commodity electronic components (Tang and Stylios 2006). Design concepts take advantage of classical textile qualities, such as comfort and fashion. While the properties of textiles can be easily customized they should not be compromised by integrated electronic components. For example, e-textiles should withstand laundering. Thus, a redesign of electronic components is needed to match their properties with those of textiles. Electronics must become resistant to water, detergents, and mechanical stress (Marculescu et al. 2003; Mecheels et al., 2004; Stylios, 2007). Electronic engineers seek to develop electronic components that are soft, flexible, stretchable, water resistant, and fit seamlessly into surrounding textiles. Microsystems technology, organic semiconductor materials, and nanotechnology are enabling technologies that facilitate the general innovation trend of seamless integration of electronics and textiles (Kind and Bovenschulte 2006).

Sophisticated e-textiles that host ICT-devices and their peripheral equipment are currently in a laboratory stage of development. Some researchers pursue design concepts that aim at deep integration of wearable computing devices into clothing (Buechley 2006). That will render separate ICT devices unneeded. Textile-embedded human-computer interfaces (e.g. switches, dials, keyboards, flexible displays) provide superior usability and comfort (Marculescu et al. 2003; Park and Jayaraman 2003). Others comprehend wearable computers as detachable objects such as headsets, glasses, buttons, rings etc., forming a body-centred network, which is mounted on clothing (Starner 2001). Three successive steps of innovation can be delineated with regard to design concepts of integrating electronic components into textiles (figure 3-1) (Mecheels et al. 2004; Cho et al. 2010):

1. Adoption: distinct electronic devices are embedded into a textile platform (e.g. incorporated into pockets). Such products were already introduced into the market in the form of mobile phone periphery devices.
2. Seamless Integration: electronic devices are to be incorporated throughout textile materials (e.g. embroidered sensors, laminated circuit boards). This is the current stage of the innovation process.
3. Combination: textile materials and structures with inherent electronic functionality (e.g. yarn transistor, fibre based circuits, photovoltaic fibres).

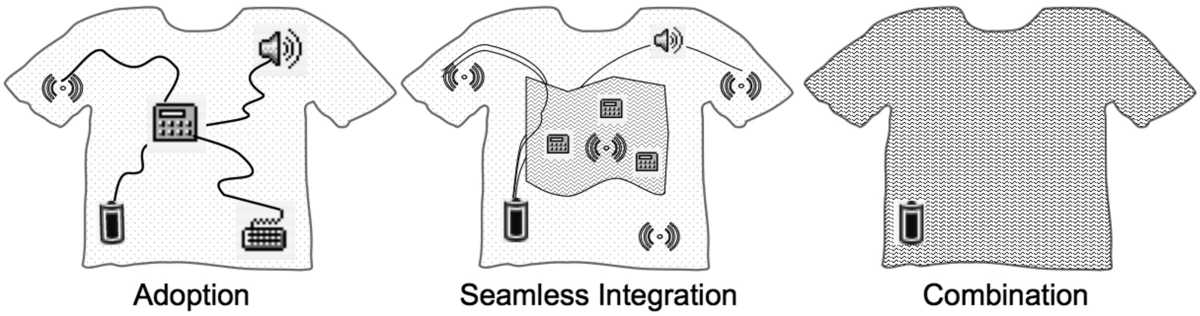


Figure 3-1: Design concepts of converging electronic and textile components (symbolic sketch).

3.2.2. Market Perspectives

For the time being, e-textiles exist in specialized niche markets (e.g. health care and work wear applications). This first generation of e-textiles is leading the innovation process. The proliferation of sophisticated e-textiles at consumer mass markets is expected to take more time. Observers of the innovation process expect that e-textiles will penetrate mass markets within the decade (McWilliams 2007; Stork 2008). In particular the market segments of sports clothes, tele-medicine, and lifestyle textiles hold potentials for mass application (Stork 2008). Results from our expert survey among e-textile developers indicate current hot-spots of innovation (figure 3-2, left). The estimation of the possible market size varied depending on the respective application area (figure 3-2, right). For the near future, the interviewees expected the highest market potential in the area of ambulatory health monitoring.

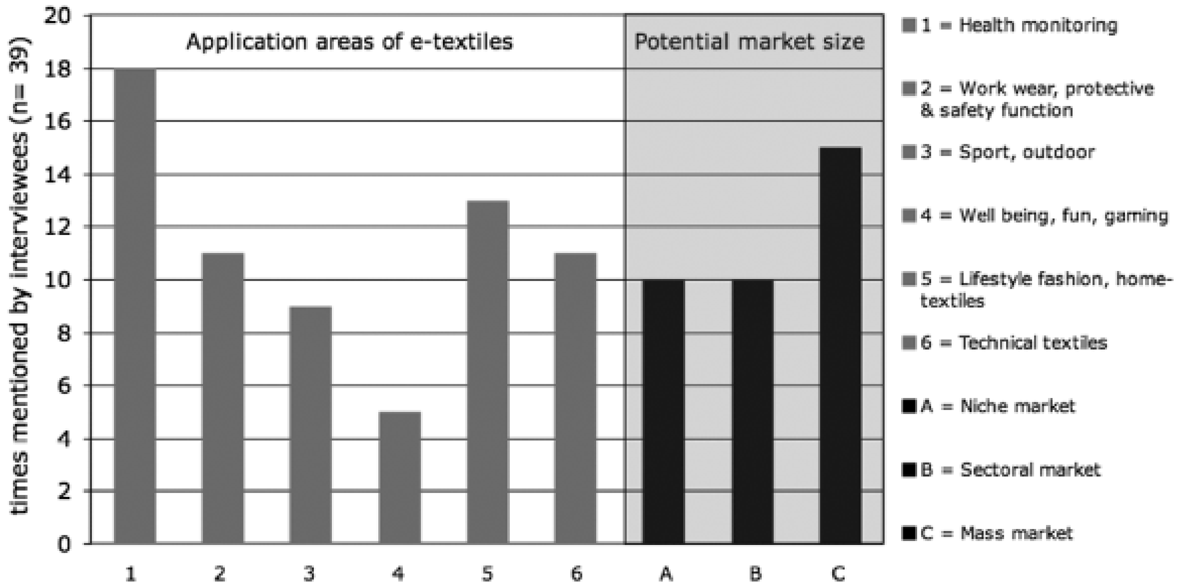


Figure 3-2: Expert expectations on application areas (left) and market size (right) of e-textiles. Definitions: the time horizon is one decade; niche market = high value-added specialty products (e.g. fire-fighter suits); sectoral market = customized applications (e.g. tele-health monitoring); mass market = ubiquitous consumer applications (e.g. casual apparel). Source: own data.

3.2.3. Materials and Components used in E-textiles

The first generation of e-textiles contain a similar range of materials as today's commodity electronic products. The latter usually contain considerable amounts of valuable materials, which reside mainly in the devices' printed wiring boards (PWB) (Huisman 2004; Chancerel et al. 2009; Schluep et al 2009). In addition, electronic products are known to contain hazardous substances or their precursor substances (Chancerel and Rotter 2009). Mobile phones, for instance, contain valuable metals such as copper, silver, and gold, as well as problematic substances in batteries, and plastic additives (e.g. flame-retardants).

The electronic components in first-generation e-textiles are made of off-the-shelf technology, e.g., arrays of small, light-emitting diodes. These parts are spread out across textile surface areas. Electronic circuits can either be sewn on fabrics directly or mounted on flexible PWBs, which must be compatible with classic textile properties (that is, stretchable, elastic, and waterproof). Flexible PWBs often consist of polyamide foil coated with nickel/copper layers that are plated with thin gold layers to allow for good electrical contacts. Flexible PWB can be sewed, laminated, or glued onto fabrics. Casing and packaging of electronic components are made of fabric or plastic foil rather than of steel, aluminium, or bulky plastic parts. Thus, e-textiles contain smaller amounts of such construction metals whereas certain specialty metals may gain in relative importance. Silver, for instance, is a candidate for more widespread usage.

If the design concepts 'integration' and 'combination' (see figure 3-1) become reality, one can expect more significant changes in the materials composition. Then, textile electronics will consist of embroidered circuitry and organic electronic components, which can be printed directly onto the fabric surface. Electronic components will tend to become smaller and more scattered across the textile. Moreover, electronic and textile materials will become more and more amalgamated. Polymer-metal composites and nano-materials may replace traditional electronic materials. Table 3-1 provides an overview of electrically active components of e-textiles that are currently in the focus of research and development.

Table 3-1: Examples of electronic components and materials that are integrated into textiles.

Examples of electronic components in textiles	**Application**
Electrically-conductive fibres and sheets	- Electrostatic dissipation and electromagnetic shielding - electric interconnection and power distribution - sensor and actuator elements - heating resistors - transmission of analogue and digital signals - radio-frequency antennas
Optical fibres	Light dispersion, signal transmission,
Soldering joints, bonding pads, mechanical contacts	Electric contacting and mechanical fixation
Flexible wiring boards and embroidered wiring	Mechanical fixation and electric interconnection of electronic components, protection against wear and tear
LEDs, OLEDs, laser diodes and flexible displays	Lighting, photonic effects, user interaction
Digital devices, such as mp3-player, micro-controller and networking units.	Information and communication functions, interactivity and smartness
Embedded periphery: dial pad, speaker, micro-phone, radiofrequency antenna, RFID-tags	User interaction, data input and output, wireless network connection
Solar cells, piezoelectric units, thermoelectric generators	Power generation (harvesting from ambient energy sources such as light, heat, mechanical movements)
Rechargeable batteries	Power storage

LED – light-emitting diodes; OLED – organic light-emitting diodes

The following sub-sections provide a glimpse into the materials inventory of some enabling technologies of e-textiles (Köhler 2008).

3.2.3.1. Electrically-conducive Fibres and Interconnections

To establish electrical interconnections, developers of e-textiles normally use metallised fibres or yarns, containing silver, copper, or nickel (table 3-2) (Berzowska and Bromley 2007; Meoli 2002; Mythili et al. 2007). The metal content of commercially available conductive yarns can be up to 40 $\%_{wt}$. Solid metal strands and wires of stainless steel are used as well but they are less flexible and less comfortable to wear. Alternatively, conductive fibres can be made of intrinsically conductive polymers, such as polyaniline (Kim et al. 2003; Kim and Lewis

2003). Some developers experiment with conductive composite fibres that contain metallic particles or carbon particles (Lübben 2005). Also nano-composites with 0.5 to 20 $\%_{wt}$ carbon nanotubes (CNT) in the polymer matrix show sufficient electrical conductivity for certain applications of e-textiles (Köhler et al. 2008). Cotton yarn can be made electrically conductive by coating them with polymer stabilized CNT (Shim et al. 2008; Avila and Hinestroza 2008).

Table 3-2: Overview of materials used to enhance conductivity of textiles. Source: (Köhler 2008)

Material	**Integration in textiles**	**Percentage of conductive material***	**Production technology**
Metals			
Cu / Ag /Au	Cu wire plated with Ag or Au single wire or strand blended/wrapped yarn or fabric	up to 100 $\%_{wt}$	Spinning, interweaving Stitching, sewing
Stainless steel	single wires or threads spun into yarn	up to 100 $\%_{wt}$	Spinning, interweaving Stitching, sewing
Ag / Cu /Au / Ni	coating of fibre or fabric surfaces.	1-40 % of fibre weight	Chemical deposition
Ag	coating fabric surfaces.	metal content in the ink up to 70 $\%_{wt}$	Screen printing, Ink-jet printing
Cu / Ag /Au / Al / Ti etc.	fibre of fabric coating	< 0.5 $\%_{wt}$	sputter deposition, plasma coating
Conductive polymers			
Polyaniline (PAni) Polypyrrole, Polythiophene	Conjugate polymer fibres or bi-component (core/shell) fibres	up to 100 $\%_{wt}$ PAni in the shell of coated polyester fibres	solvent casting, melt spinning Conjugate spinning
Nano-particles			
Carbon nanotubes single-walled or multi-walled (in the future)	pure CNT yarn CNT-polymer composites coating of fibre, yarn coating of fabric surfaces	approx. 100 $\%_{wt}$ 0.1-0.5 $\%_{wt}$ CNT in polymer composites	Spinning In situ polymerization melt-spinning and annealing of polymer coated CNT Wet dying Ink-jet printing
Carbon black	Filler of polymer fibres Surface coating of cotton fibres	50$\%_{wt}$	Melt spinning, Wet spinning Printing, wet coating
Nanoparticulate silver	coating of fibre or fabric surfaces.	n.a.	Plasma coating, Sol gel process
Others			
optical glass or plastic	optical fibres mechanically attached	n.a	sewing, stitching

* Material content refers to the intermediate material (e.g. yarn, fabric). No data were available for final products.
Glossary: Al – aluminium; Ag – silver; Au – gold; CNT – carbon nanotubes; Cu – copper;
PAni - Polyaniline; Ti –titanium; n.a. – not available.

3.2.3.2. Contacting and Bonding Elements

New technological solutions are being developed for mechanical fixation of electronic components and their interconnection within textile materials. Electrical contacts must withstand harsh external impacts during use phase (washing, drying, mechanical abrasion, humidity, chemicals and UV-radiation etc). Those factors limit the useful lifetime of e-textiles (measured in washing cycles). The following list summarizes the state of art for electrical contacting technologies.

- Soldering: based on lead-free solders (alloys of tin, silver, copper, antimony, bismuth).
- Mechanical connections: Embroidery of conductive yarn. Metallic snap fasteners or metallised hook-and-loop fasteners are used for detachable connections.
- Conductive adhesives that contain metallic particles (typically silver) or carbon black dispersed in monomers/polymers (e.g. (poly)urethane) or bi-component epoxy resins (Healy et al. 2003; Kolbe et al. 2005).

3.2.3.3. Power Supply

E-textiles are mostly powered by lithium-ion batteries. They can be recharged either by means of grid-connected chargers (requires user interaction) or by solar cells, thermo generators, piezo elements – harvesting ambient energy (Kim and Lewis 2003). Batteries are embedded into textiles in such a way that they can be detached before laundry. Some developers have created waterproof batteries, which can be seamlessly embedded into textiles (non-detachable).

3.3. Estimation of Future E-textile Waste Streams[24]

E-textiles will inevitably turn to waste at the end of their useful lives. Contemporary electronic products usually have rather short service lives. There is no reason to assume that e-textiles will break with that trend. On the contrary, their obsolescence may even be accelerated due to fleeting fashion trends in the apparel sector. One can expect that old e-textiles will cause large waste streams similar as today's e-waste.

To estimate the order of magnitude of future waste streams, the possible market diffusion trend of e-textiles was extrapolated in scenarios. A base scenario of market diffusion was conceived by projecting historic data on market diffusion of small high-tech devices, such as mobile phones, into the future. The scenario represents a case study of the national German market. It was assumed that the market diffusion of e-textiles will follow a sigmoid growth curve similar to the mobile telecommunication market in the past. That market segment grew from 10% to 90 % of the maximal market size (K) within a period of nine years (for details, see

[24] The prospective waste stream of e-textiles was estimated by means of trend extrapolation and analogy. For this purpose, a base scenario of market diffusion was set up in form of a sigmoid market growth model (Boretos 2007). That base scenario was calibrated with data derived from a case study on the market diffusion of mobile phones in Germany. On top of the base scenario, three application scenarios of e-textiles were developed characterizing their technical properties and useful lives. Lessons learnt from the contemporary e-waste problem served as a general yardstick for analysis. This information was obtained from literature. Further details of the scenario development are explained in the supporting information available on the Journal's Web site.

section 3.6.). With the base scenario in the background, three different application areas of e-textiles were considered. Table 3 gives an overview of the key parameters presumed for the application scenarios.

A) Niche market: Fire-fighter suits with integrated sensors, data processing unit, navigation system, radio transceiver, and batteries.
B) Sectoral market: ECG-shirt (electrocardiograph) with integrated sensor pads & radiofrequency-antenna used for constant heart monitoring (tele-health monitoring).
C) Mass market: Outdoor jacket with integrated mp3-player, mobile phone, dial-pad, flexible solar cells, and batteries.

Table 3-3: Specifications of the application scenarios

Scenario name	**A) Fire-fighter suit**	**B) ECG-shirt**	**C) Outdoor jacket**
Market type	niche market	sectoral market	mass market
Application area	protective wear	health monitoring	everyday life
Maximal number of users	K = 300,000 [II]	K = 27 million [III]	K = 82 million [IV]
Number of units per user [I]	1	7 (one per day of week)	2 (one summer jacket / one winter coat)
Average product lifetime [I]	5 years	1 year (50 laundries)	3 years (three fashion seasons)
Weight per unit [I]	2000g	130g	800g / 1200g
Weight of the electronic components at beginning [I]	250g	10g	50g

[I] Parameters based on own assumptions;
[II] Number of fire-warden offices times ten;
[III] All citizen of age 55+;
[IV] Whole German population. Source of demographic data: (Destatis 2010)

The amount of waste per year from each type of e-textile was extrapolated on the basis of the three application scenarios. Figure 3-3 shows the extrapolated waste stream of complete e-textiles (electronic components together with textile materials). Significant amounts of waste emerge approximately 5 to 7 years after the first introduction of e-textiles at the mass market. Figure 3-4 shows the extrapolated mass stream of electronic components only, as if they were separated from the textiles. In each scenario, an annual 2% decrease in weight of the electronic components was presumed as an approximation for miniaturization trends.

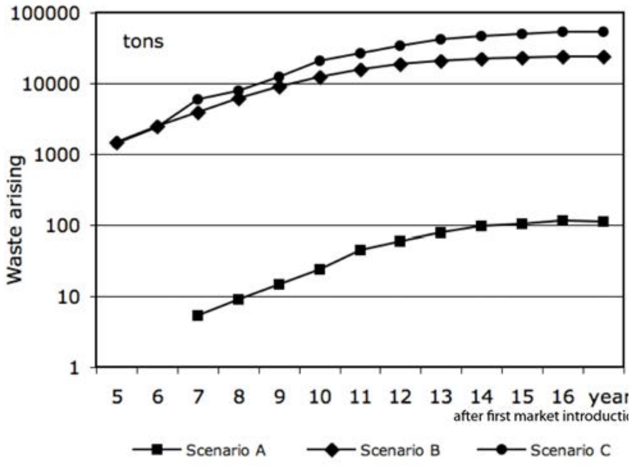


Figure 3-3: Extrapolated waste arising of obsolete e-textiles (whole product) for the three scenarios

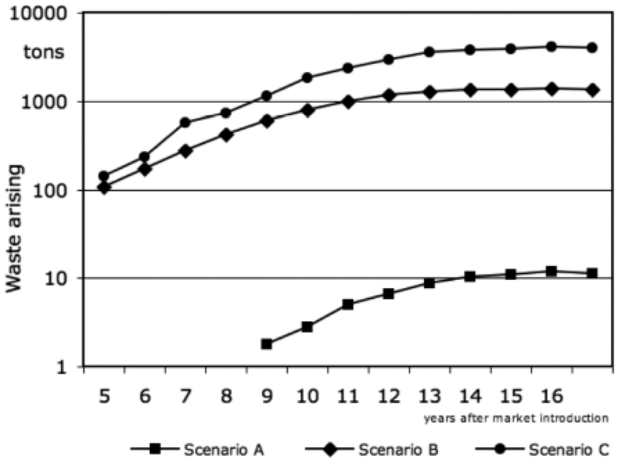


Figure 3-4: Extrapolated waste arising of textile-embedded electronic components for the three scenarios (A - fire-fighter suit; B - ECG-shirt; C - Outdoor jacket).

The case study shows that the extrapolated waste stream of old e-textiles in Germany can grow as high as 24 kilotonnes (ktonnes)[25] per year in scenario B (ECG-shirt) and 55 ktonnes in scenario C (outdoor jacket). Textile materials contribute the biggest portion by weight within that waste stream. The e-textile waste stream in the mass-market scenario C would constitute approximately 5% of weight among the 1.13 million tonnes of discarded clothes and home textiles in Germany (BVSE 2009). While old e-textiles may not result in a massive increase of the domestic textile waste stream, they can change the material composition of the recyclable fraction of old textiles.

Electronic components may have a concentration between $7\%_{wt}$ in scenario B and $15\%_{wt}$ in scenario A (fire-fighter suit), the rest consists of textiles or plastic/metal parts (e.g. buttons etc.). The e-waste fraction in the textile waste stream is estimated with 1,300 tonnes per year in scenario B and 4,000 tonnes in scenario C. The flow of textile embedded e-waste does not appear significant when compared with the total textile waste flow. However, it has the same order of magnitude as obsolete mobile phones have today in Germany (see the data in appendix S1 in the supporting information (section 3.6. for comparison).

The prospective arising of old e-textiles on a global scale was estimated with one million tonnes per year as an order of magnitude. That waste stream would contain 50 to 150 ktonnes embedded electronic components, depending on the type of e-textiles.

3.3.1. Discussion of the Scenarios

E-textiles can form a considerable waste stream provided that they evolve as mass-applications. Scenario B illustrates that this is also possible in sectoral application areas such as health care. We consider our market diffusion scenario a rather conservative estimate.

[25] One kilotonne (kt) = 103 tonnes (t) = 103 megagrams (Mg, SI) ≈ 1.102 x 103 short tons.

There are several reasons to assume that the future market diffusion of e-textiles can be at least as rapid and widespread as the one of mobile phones in the past.

Firstly, the time span in which the market diffusion of e-textiles grows from 10% to 90% of the total market size can be briefer than it was with mobile phones. The diffusion of mobile communication technology was largely determined by co-creation of the backbone infrastructure (e.g. mobile telecommunication networks). E-textiles, in contrast, can take advantage of already existing wireless network infrastructure and some types of e-textiles can be used as stand-alone devices.

Secondly, e-textiles are likely to co-exist in multiple applications areas. The technology vision of pervasive computing suggests that users possess numerous devices simultaneously. Different types of e-textiles can be used at the same time, given their broad variety of functions. Stand-alone devices (e.g. mp3 players) may be used in addition to networked devices (e.g. smart phones). On the other hand, consumers possess multiple clothes and use them infrequently (e.g. seasonal). That means users may possess numerous e-textiles but not use these items all the time.

Thirdly, we presumed a general miniaturization trend of single ICT devices. That trend has been observed throughout the history of the ICT sector, for instance in case of mobile phones. However, miniaturization has almost always been outweighed by growing numbers of devices used. The effect has become known as the "*miniaturization paradox*" (Hilty 2008). There is no reason to expect that e-textiles will break with that trend. The results of our scenarios suggest that the waste flows of e-textiles will increase in spite of their miniaturization.

3.4. Recyclability of E-textiles[26]

This section presents a brief discussion of the capability of recycling and disposal schemes to cope with old e-textiles. The fate of old e-textiles will depend on the waste management schemes that are established at the place of their disposal. They differ largely among different countries (Schluep et al. 2009). Figure 3-5 summarizes principal recycling or disposal processes of e-textiles.

[26] A broad review of scientific literature and contributions at conferences/industry fairs regarding expected end-of-life implications of e-textiles was undertaken. However, no such information could be found by literature review. Therefore, a second batch of interviews was conducted with six experts from recycling firms of both sectors, e-waste recycling and textile recycling. The interviewees were presented the properties and materials of e-textiles and then asked open-ended questions. These interviews purposed to explore the experts' opinions about the recyclability of e-textiles.

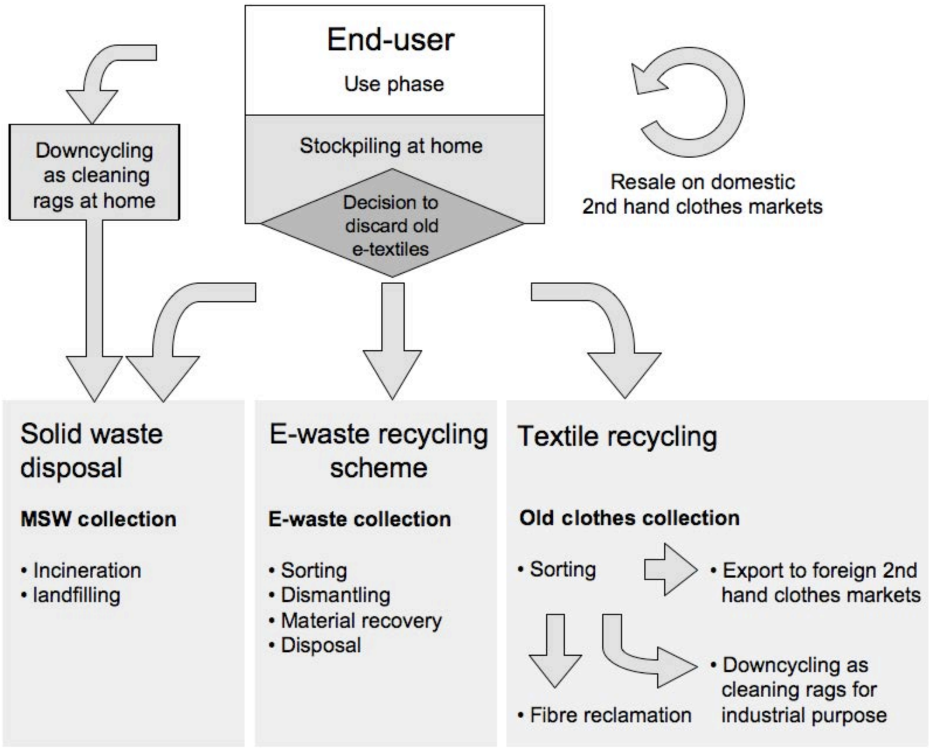


Figure 3-5: Possible recycling and disposal channels for e-textiles Source: (Köhler 2008)

Currently established recycling schemes are inappropriate to collect and process textiles with integrated electronic components. From the present-day perspective it can be assumed that the biggest fraction of discarded e-textiles would be disposed of together with municipal solid waste (MSW). In principle, MSW disposal is done either by incineration or by direct landfilling, depending on the country. If e-textiles are co-incinerated with MSW, recovery of valuable materials is hardly possible with today's technology. Metal recovery from incinerator bottom ash is only possible for larger metal parts - roughly in the centimetre range (Morf et al. 2009). Metallic components found in e-textiles (such as silver coated fibres) have a much smaller size. Therefore, co-incinerating e-textiles would disperse the valuable metals, such as silver, in the bottom ashes or in the filter dust. The latter is disposed of as hazardous waste. Hence, textiles will contribute to the contemporary environmental problems of disposing e-waste together with solid waste (Jang and Townsend 2003; Gullett and Linak 2007).

3.4.1. E-textiles entering an E-waste Recycling Scheme

Discarded e-textiles may find their ways into recycling schemes for e-waste (Waste Electrical and Electronic Equipment, WEEE). With the WEEE Directive in effect since 2005, European countries are supposed to implement schemes for separate take-back and recycling of WEEE (EC 2003). E-textiles, however, being not explicitly addressed by that regulation, would be rejected at the collection points or sorted out by recycling companies. That holds true unless the legislature includes e-textiles the regulation or material recovery from e-textiles emerges as a profitable business (the latter appears possible in developing countries, resembling today's informal e-waste recycling (Puckett et al. 2005)). Sorted out items are usually disposed of as solid waste. From the technical perspective, the established WEEE take-back and recycling systems are not designed to deal with this novel type of waste. In general, they exhibit very poor performance for e-waste items below one kilogram (Huisman et al. 2007). The recycling experts interviewed deemed it difficult to recycle e-textiles. They expected various technical problems. Textiles could jam shredders and crushers such as currently used in WEEE recycling. Automated separators were seen inadequate to separate fluffy lightweight materials such as metallised plastic foils and textile fibres. From current WEEE recycling technology is known that mechanical shredding results in great losses of precious metals. A large part of these materials are transferred into output fractions from which they cannot be recovered (Chancerel et al. 2009). Likewise, shredding e-textiles would transfer the precious metals (e.g. silver) into the dust fraction.

The experts deemed manual sorting and processing of e-textile waste possible although difficult. The processing costs were estimated to be prohibitively high because the valuable metals are not concentrated in PWBs as in traditional WEEE. The interviewees pointed to the serious challenge of taking into account the heterogeneity of textile products as well as the specific design features of e-textiles (unobtrusiveness). Personnel at collection points and recycling workshops would need to be trained to recognize miniaturized electronic devices that are seamlessly integrated in textiles. Moreover, investments would be necessary in regard to storage, transportation, and appropriate tools to process old e-textiles.

3.4.2. E-textiles entering a Recycling Channel for old Textiles

The last owners of old e-textiles are assumed to dispose of the old e-textiles together with ordinary old clothes rather than as e-waste because the electronic parts are unobtrusive. Collection of post-consumer textiles is often performed by charities or recycling firms. Collection rates of old textiles are usually low, e.g. 17% in the UK (Morley et al. 2006). The larger share of the collected old textiles is exported to developing countries where they are re-used and eventually disposed of (Waste Watch 2006). Shipments of old textiles to foreign markets are 54% in the UK and 41% in Germany (BVSE 2009). One third of old textiles in Germany (233,000 tonnes per year) are inputs to fibre reclamation processes to produce felt or fabric for industrial purpose.

The extrapolated arising of old e-textiles would constitute a minor fraction of the whole old textile stream - approximately 5% as for scenario C. In Germany, discarded clothes and home textiles form an annual waste stream of 1.13 million tonnes (BVSE 2009). Old e-textiles are likely to appear at the second-hand clothing market, for they may still provide textile functions after the smart function has ceased to be useful. In this case, the larger part of old e-textiles will be exported overseas as part of normal second-hand clothes. Before shipment, the textiles are baled by applying mechanical force. Batteries contained in old e-textiles could cause a fire hazard if not removed before baling. The end-of-life fate of e-textiles reused in developing countries is hardly predictable. However, one can assume that the content of precious metals (e.g. silver) may trigger a backyard recycling under similar poor environmental and occupational health conditions as known from e-waste recycling.

E-textiles could also enter sophisticated fibre reclamation processes based on mechanical shredding. Waste electronic materials can be regarded as contaminants in the textile waste stream as they are widely dispersed within discarded clothes. There is a risk that e-textiles could disturb these processes or contaminate the secondary fibres produced. Cross-contamination of other recycled materials (such as synthetic fibres) lowers the market value of the latter. Moreover, co-processing of old e-textiles in fibre recycling can pose unexpected emissions of dust containing heavy metals. It can cause occupational health and environmental problems like the dust released from e-waste shredding (Hanke et al. 2000). Removal of components containing hazardous substances would be necessary prior to fibre reclamation. The interviewees from textile recycling businesses deemed that additional step difficult and costly.

3.5. Conclusions and Recommendations

We portrayed e-textiles as an example of pervasive computing technologies. These products can cause end-of-life problems in the future due to the following reasons:

- E-textiles will likely be used as mass appliances and can result in large waste streams.
- It will be difficult to collect and recycle old e-textiles by means of contemporary collection and recycling schemes.
- Valuable materials contained in e-textiles are dispersed within textile bulk materials, making e-textiles a low-grade feedstock for metal recycling. Fibre recycling, in turn, is seriously compromised by e-waste contaminating the textile materials.
- The possible content of problematic substances (or their precursors) in e-textiles poses environmental and health risks in recycling and disposal processes.

At present, not even contemporary e-waste, having a relatively high content of valuable metals, is recycled at sufficient rates. There is no reason to expect sufficient recycling rates with low-grade waste such as old e-textiles. Hence, the industrial ecology community is confronted with the prospect of a new generation of high-tech products undermining one of the core ideas of industrial ecology: closing material loops (Ehrenfeld 2008).

From this background, we regard it crucial to implement waste preventative measures, i.e., design for recyclability, integrated in the innovation process of e-textiles. Later on, opportunities for fundamental solutions wane and technical ‘quick fix’ solutions are applied at best, curing only symptoms of the problems. This is because corrective action, such as redesign, becomes too difficult and expensive once that a technology reaches a large market penetration (Collingridge 1980).

This prompts a challenge to launch waste preventative measures before adverse end-of-life impacts become obvious at a large scale. E-textiles developers should therefore scrutinize the design concept of seamless integration. The technology should not be used for producing short-lived consumer products. Moreover, technology developers and product designers of e-textiles should not simply delegate responsibility for the end-of-life phase of their inventions to the recycling sector.

Ehrenfeld (2008) suggests turning the problems into opportunities by designing technical artefacts in such ways that they yield supreme sustainability benefits over their whole product life cycle. ICT can, like no other technology, be part of the solutions that we need to reduce the material intensity of the economy (Hilty 2008, Hilty and Ruddy 2010). We believe that e-textiles bear a great potential in this regard. As they offer radical new ways of human-technology interaction they can be designed to persuade their users to commit to a more sustainable behaviour. However, these possibilities are unlikely to unfold in a business-as-usual mode of innovation. Sustainability benefits must be searched for and proactively put into practice.

Industrial designers can play a vital role here as they can create showcases of sustainable e-textiles. That way they can inspire consumers and decision makers in industry to turn their attention towards sustainable alternatives. It remains to be demonstrated that e-textiles can indeed fulfil sustainable functions while keeping the end-of-life and other sustainability risks in check. To industrial designers we recommend adopting the principles of green engineering as a modus operandi of taking responsibility for the life-cycle-wide environmental impacts of e-textiles (Anastas and Zimmerman 2003).

To prompt sustainable innovation of emerging technologies, the legislature should send clear signals to research institutions and industry. The revised European Eco-design directive (EC 2009) could serve as a model as it mandates eco-design requirements for the development of energy-related products. Likewise, waste prevention should be made an explicit goal of innovation strategies. The US EPA has outlined possible ways to move forward with sustainable management of materials by incorporating life-cycle thinking into the design process of future products (EPA 2009). In addition, recyclability-targets should be mandated in the framework of innovation funding schemes that support the developers of e-textiles.

3.6. Supporting Information

A market diffusion scenario of e-textiles was extrapolated by analogy with the market diffusion of small information and communication technology (ICT) devices based on historical data. Past innovations in the ICT sector have demonstrated that high-tech products can diffuse onto mass markets rapidly (Lee and Lee 2009). Mobile phones were chosen for comparison with e-textiles as they represent small high-tech products that fit into the concept of wearable electronics.[27] Since the first mass-produced GSM[28] phone was sold in 1992, their market diffusion has been increasing continuously. Currently, the penetration of equipment in the mo-

[27] Modern smart phones are multifunctional devices that can operate in different modes: A) in a network service mode (wireless telecommunication via GSM, UMTS, Bluetooth, W-LAN) and B) stand-alone mode (e.g. digital camera, digital music player, GPS device). Likewise, e-textiles can serve as interchangeable peripheral for smart phones (user-interfaces for gaming (sensor glove); wearable dial pads for sport or health-care applications) as well as stand-alone devices (e.g., sport heart-rate monitor, luminescent garments).

[28] Global System for Mobile Communications (GSM)

bile communication sector is up to 100% in many countries (that is a complete market saturation). [29]

As a case study, the national German telecommunication market was analyzed because comprehensive statistical data on market diffusion were publicly available (BITKOM 2010). Moreover, that country represents one of the biggest telecommunication marketplaces among European countries and can therefore be considered representative. Similar patterns of market diffusion and waste arising have been observed in numerous countries worldwide (Fishbein 2002). Figure 3-6 shows the historical development of mobile service subscriptions over a period of 15 years after market introduction of GSM networks in Germany. Subscriptions were considered as a proxy for the market penetration of mobile phones. It was assumed that the market diffusion of mobile phones obeys a sigmoid growth model according to equation (1) (Boretos 2007). Figure 3-6 shows the calculated growth curve superimposed to the observed market growth.

$$N_u(t) = \frac{K}{1+\exp\left[\frac{-\ln(81)}{\Delta t} * (t - t_m)\right]} \qquad (1)$$

$N_u(t)$ Number of users (market penetration) over time.

K Maximum market capacity.

$\triangle t$ Time (in years) needed for N_u to grow from 10% to 90% of K.

t_m Time at which market penetration (K) is 50%.

The arising of obsolete mobile phones in Germany (figure 3-7) was calculated assuming useful lives of 2.5 years on average (BITKOM 2010). Obsolescence was presumed to be 25% for two years old devices, 75% after three years, and 100% after four years (equation (2)).

$$N_O(t) = 0.25 * Nn_{t-2} + 0.5 * Nn_{t-3} + 0.25 * Nn_{t-4} \qquad (2)$$

$N_O(t)$ Number of obsolete devices over time.

N_n Number of new devices shipped to the market over time.

t Time (in years).

[29] In many industrialized countries, multiple mobile subscriptions per user are commonplace (the so called “Double-SIM” effect) resulting in a degree of equipment higher than 100% (ITU 2009). That effect has been observed at the mobile telecommunication market since 2003 and has caused a new growth cycle (Boretos 2007).

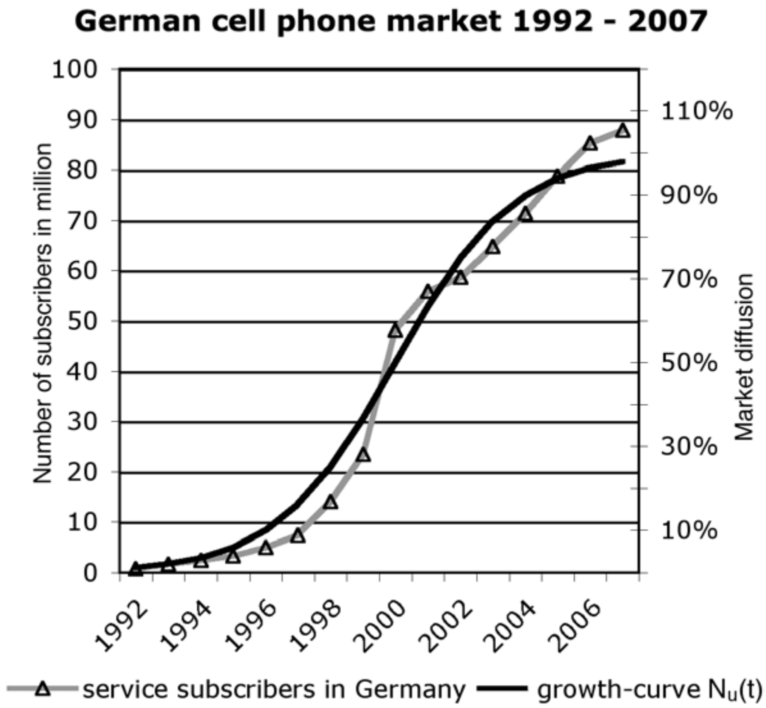
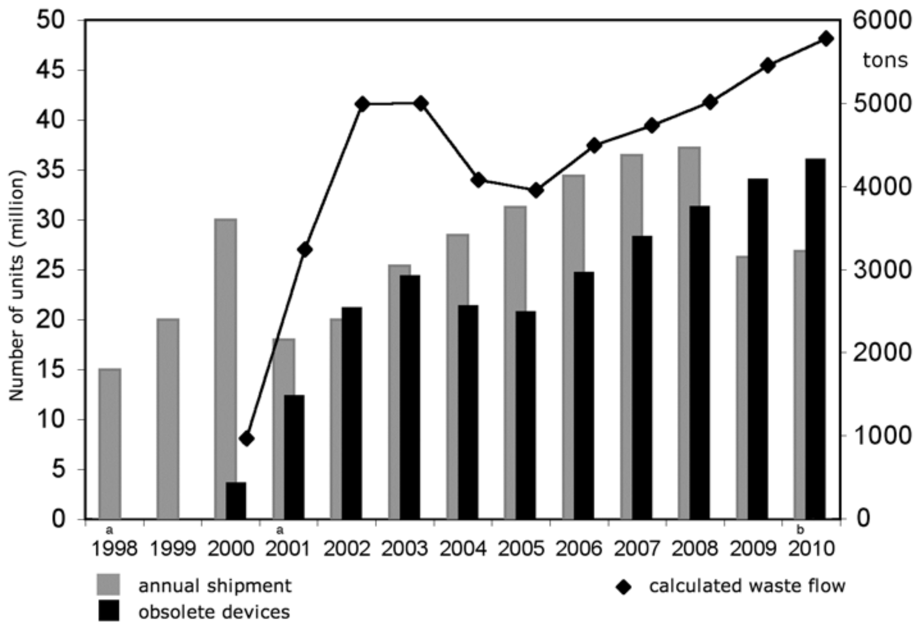


Figure 3-6: Growth of the mobile phone market in Germany: Numbers of cell-phone subscriptions Source of data: (Federal Network Agency 2010).

The resulting waste stream of mobile phones (figure 3-7) was calculated assuming average weight of 160g per obsolete device (BITKOM 2010; Chancerel and Rotter 2009).

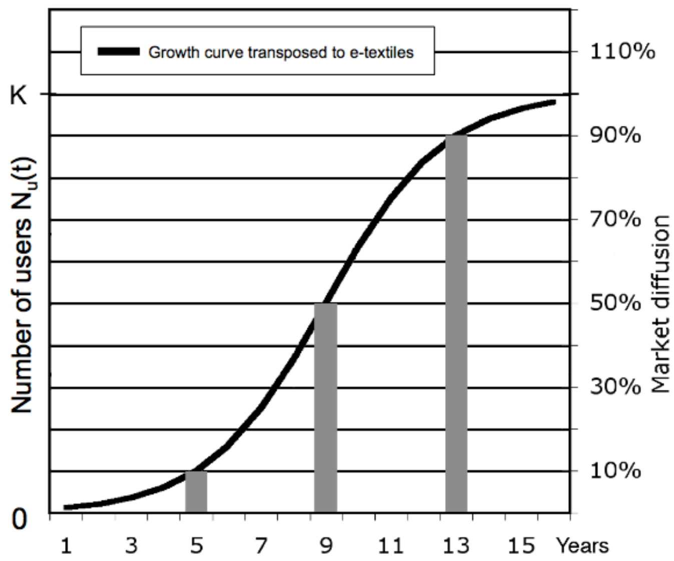


*a – own estimate, *b – forecast.

Figure 3-7: Shipments of mobile phones and estimated arising of WEEE. Sources: (BITKOM 2010; Chancerel and Rotter 2009).

A larger weight was assumed for older devices (including charger): 260g for items produced before year 2000; 190g for those produced from 2000 to 2004. The fate of end-of-life mobile phones is uncertain. Only a small percentage of them appear in official e-waste recycling schemes. End-users tend to stockpile obsolete mobile phones for some time before discarding them (Nokia 2008). Therefore, in reality the actual arrival of end-of-life mobile phones in the waste stream is delayed. It is believed that used high-tech devices are often exported to developing countries as part of second hand commodities (Puckett et al. 2005; Sander and Schilling 2010).

A base scenario of the future market diffusion of e-textiles was set up by projecting the historical growth curve of mobile phones (figure 3-6) into the future (figure 3-8). It was assumed that e-textiles, like mobile phones, might saturate the market. That is, within a certain market segment, almost all potential users will eventually use them. In the scenario, it takes the e-textiles market nine years to grow from 10% to 90% of the maximum market size (K). The base scenario served as background for anticipating the arising of old e-textiles (figure 3-9) in the scenarios of different application areas (A - fire-fighter suit; B - ECG-shirt; C - Outdoor jacket).



$N_u(t)$	10% K	50% K	90% K	K
Scenario A	30,000	150,000	270,000	300,000
Scenario B	2.7 million	13 million	24 million	27 million
Scenario C	8.2 million	41 million	74 million	82 million

Figure 3-8: Market diffusion scenarios of e-textiles in Germany. K - Maximum market capacity. (Scenarios: A - fire-fighter suit; B - ECG-shirt; C - Outdoor jacket).

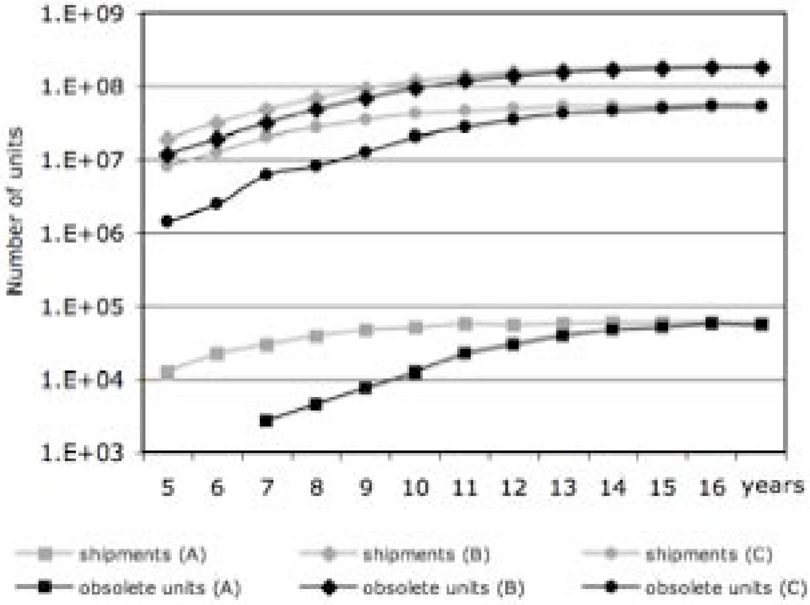


Figure 3-9: Extrapolated numbers of obsolete e-textiles per year in Germany for the three scenarios (A - fire-fighter suit; B - ECG-shirt; C - Outdoor jacket).

The prospective arising of old e-textiles on a global scale was extrapolated in the same way as the case study on the historical mobile phone market in Germany. The calculation was done on basis of comparison to the worldwide shipment of new mobile phones (including smart phones) in 2009. In that year 1,383 million units were sold worldwide (Gartner 2010). That number is commensurate with a total mass of approximately 200 ktonnes.

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CHAPTER 4

Risk Preventative Innovation Strategies for Emerging Technologies The Cases of Nano-Textiles and Smart Textiles

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4.1. Introduction

Nanotechnology and pervasive computing are hot spots of current technological innovation. The emerging technologies have unleashed exciting prospects for business opportunities and job creation (Sear et al., 2009). Entrepreneurs and innovative enterprises aspire to innovative technologies in order to commercialise novel products. They have the objective to create economic, societal, and environmental benefits (Reinert et al., 2006). But there also are concerns over the possible adverse impacts of these emerging technologies on the environment, human health & safety, and sustainability (EHS/S).

Innovative enterprises should identify possible side effects and manage these risks concurrently to the technology development process (Som et al. 2011; Helland et al., 2008; Hull. 2010). Enterprises are used to deal with tangible risks as part of their business processes. Risk management is a regular part of the product development process because businesses bear stewardship for their products. New product development therefore includes the assessment of technical and electrical safety, fireproofing, and biocompatibility etc. Safeguard measures are taken in accordance to the requirements of regulations or technical standards, such as the mandatory CE (European Conformity) marking for a wide range of safety relevant products (European Commission, 2011). In mechanical engineering projects for the European market, for instance, it is obligatory to assess the safety risks by provision of the EU machinery safety directive (06/42/EC), by using failure modes and effects analysis (FMEA) for instance (Cameron and Raman 2005).

In practice however, the EHS/S impacts of emerging technologies are hard to address by means of conventional risk analysis methods, such as FMEA and SWOT. Companies are often lacking resources to examine the prospective side effects of products (Hull, 2010). For instance, the majority of companies utilising nanotechnology adopted state-of-the-art safety measures but they were seldom able to provide nanotech specific safety information (Gerritzen et al., 2006). And, the commercialisation strategy for the European smart textiles sector does not address EHS/S aspects (Byluppala et al., 2011). Furthermore, the legal framework for the management of emerging EHS/S risks is inadequate for enterprises because legislation is usually lagging behind the technological advances.

Quite often, strategic decisions on new technology development seem to be made without taking the potential business impacts of the EHS/S side effects into account. One of the reasons is the epistemic uncertainty about failure modes and failure effects. Another difficulty is that cumulative long-term effects are typically outside the FMEA framework. A single actor can hardly model the systemic effects that emerge due to the mass application of products. Assessing complicated cause-effect chains of technologies in society and the environment requires specific expertise and access to scientific knowledge. Businesses, in particular small enterprises, often lack these competences and they have limited resources to acquire external expertise necessary for the risk assessment of emerging technologies. Hence, the question arises how companies can cope with the intangible risks of newly developed products.

The objective of this paper is to identify early warning signs for potential EHS/S risks of emerging technologies. Results of two case studies on nano-textiles and on smart textiles are combined to analyse possible adverse side effects at different stages of a product life cycle (production, use, disposal). The analysis also delineates prevailing uncertainties regarding adverse side effects. The information about warning signs can possibly support informed decision making in industry, research and regulatory agencies and help to foster sustainable technological innovation strategies. Further, we discuss prevention strategies that could support the management of intangible EHS/S risks at the early stage of technology development. These strategies can help to minimize the risks for the environment, health & safety, and sustainability (EHS/S). They contribute to the prevention of misguided investments, economic and environmental loss, and promote safe products of high quality.

4.2. Conceptual Background

4.2.1. Terminology of risks

The history of technical innovation teaches that technologies can cause adverse side effects (EEA, 2001). Harm to human health or ecosystems can arise at various stages during the life cycle of products. In this context, side effects can be seen as an unintended deviation from the objectives of a new technology and thus represent a risk as defined in ISO 31000. EHS risks are defined as the likelihood that ‘safeguard subjects’ (human health, the environment) may suffer damage due to exposure to hazardous emissions (OHSAS, 18001:2007). For established technologies, the EHS risks are usually tangible, that is: they can be identified. The possible hazards can be reasonably predicted and the magnitude of exposure can be quantified based on empirical knowledge.

This is different in the case of emerging technologies. The extent of prospective EHS/S risks cannot be exactly determined ex-ante because research on EHS/S effects is lagging behind the technological development. Prospective side effects of emerging technologies thus represent intangible risks. The cause-effect chains are seldom fully understood owing to complexity, ambiguity, or sheer lack of information. In addition, complex systemic effects often arise when advanced technologies are applied in societal and economic realities (Hilty, 2008). Risks that can amplify one another (Assmuth et al., 2010) and risk migration can cause hard-to-anticipate effects (Alcock and Busby, 2006). Sustainability risks are often characterised by complex and multidimensional phenomena, so called “wicked problems” (Coyne, 2005). Wicked problems often entail long-term implications and non-linear behaviour (Kates, 2001) and they have a political/societal dimension, which can “not be solved by the mere application of technical/scientific methods” (Ehrenfeld, 2008 p167).

In the business context, the meaning of ‘risk’ differs from EHS/S risks: Enterprise risks refer to the possibility that an innovation project does not result in the desired outcome. An undesired outcome can include delay of product commercialisation (mar¬¬ket risk), liability and insurance costs, and also damage to the reputation of a brand. The latter can happen, for instance, due to the societal response to adverse side effects of a new technology. Companies in the nanotechnology sector are afraid of a backlash in consumer acceptance, which is perceived as a major threat for innovation (Köhler and Som, 2008). To that end, the consequences of inadequately managed EHS/S risks of new technologies represent a potential source of enterprise risks.

In the past, the EHS/S risks of novel technologies have been underestimated rather than overestimated (EEA, 2001). Occupational health damage and environmental pollution often occurred after a new technology was used on a large scale. In the worst cases (asbestos and polychlorinated biphenyls PCBs, for instance), enormous societal costs resulted from medical care for victims, support for impaired workforce and environmental remediation. Enterprises faced economic losses due to litigation costs and casualty compensation. As a consequence, the general public perceives EHS/S risks of new technologies more critical nowadays. With hindsight, the EEA (2001) notes that the societal costs of adverse EHS/S side effects would probably have been less if early warnings about risks had been taken seriously prior to mass application.

4.2.2. Effects of Uncertainty

Due to the rapid advance of innovation it is often difficult to anticipate the consequences of novel technologies in a timely manner. At the early stage of technology innovation there is usually insufficient knowledge available. The assessment of risks is hampered because: 1.) Lack of experience or foresight regarding possible side effects (lack of empirical data) and 2.) The severity of harm and the likelihood of exposure are incompletely studied (insufficient scientific understanding). Therefore, the epistemic uncertainty is immeasurable as discussed by Knight (1921).

The uncertainty extends to the context of present and future socio-economic circumstances under which users adopt new technologies. Risks arise from complex interactions, depending on the economic, cultural, and regulatory environment in which the products are used (Assmuth et al., 2010). The exposure to adverse side effects depends on the market penetration of future products and the habits of their users, which is hard to predict. Moreover, the human exposure to side effects of technologies depends on the design of future products, which cannot be anticipated. For instance, it is suspected that engineered nanoparticles (ENP) could be released from nanoproducts and then provoke adverse EHS/S effects (Wiesner et al., 2009; Alvarez et al., 2009).

4.3. Methodological approach

Two case studies, nano-textiles and smart textiles, were examined regarding the potential EHS/S risks. We picked these two technologies because they emerge from science driven innovation processes and are now at the brink of commercialisation. The choice of textiles as a product category was guided by the fact that textiles are ubiquitous in daily life. Enormous amounts of textile products are consumed worldwide and the environmental impacts of this sector are significant (Chen and Burns, 2006). That makes for a relevant magnitude of prospective EHS/S risks. Any adverse side effect of textile-embeded technologies could entail large-scale human and environmental exposure.

Nanotechnology has already been subject to public scrutiny with regard to possible risks, and early warnings on EHS/S have been discussed. That makes nano-textiles a subject worthy of scrutiny for risk assessment. The case study on nano-textiles assessed the potential EHS/S risks of engineered nanoparticles (ENP) and other nanomaterials used in textile products.

As a first step, it was necessary to generate an overview of ENP applied in nano-textiles that are on the market today. For this purpose, a review of recent scientific literature and a survey among thirty Swiss enterprises and eleven researchers were conducted (Som et al., 2008). Additionally, experts were interviewed in order to understand the integration modes for engineered nanoparticles (ENP) in textile materials (Som et al., 2009). Finally, the status of knowledge on EHS/S risks during the whole nano-textile life cycle was assessed and compiled as guidelines for sustainable innovation in the textile industry (TVS 2011).

The case study on smart textiles assessed the prospective end-of-life risks of electronic textiles. In a first survey, thirty-eight expert interviews were conducted among European researchers and enterprises to examine the innovators' knowledge about potential EHS/S impacts of waste e-textiles (Köhler et al., 2011). The survey also looked into the state of implementation of risk-prevention measures and environmental design principles in the current innovation process. The analysis was combined with results from a second study, which explored the application of life cycle assessment (LCA) in business practice. Twenty-five European SMEs (small and medium sized enterprises) of the smart textile sector participated in this questionnaire-based survey (Bakker et al., 2011). The survey was complemented by open-ended interviews to gain insights in the company's needs regarding assessment of environmental risks during the technology development process. Table 4-1 gives an overview of the smart textiles survey.

Table 4-1: Survey of smart textile developers

	Size of firm / institution[1]	**Country**	**Function of the respondents**[2]
Survey 1 (Köhler et al., 2011) n = 38	Research institute (24%), University (55%), Micro enterprise (13%), Small enterprise (3%), Medium-sized (5%),	Austria (5%), Belgium (8%), Germany (61%), Italy (5%), UK (3%), Switzerland (16%), US (3%),	Consultant (3%), R&D (78%), Managing director (6%) CTO (13%)

Survey 2 (Bakker et al. 2011) n = 25	Micro enterprise (43%), Small enterprise (26%), Medium-sized (30%),	Austria (9%), Belgium (4%), Denmark (9%), Germany (26%), Netherlands (4%), Finland (4%), Italy (13%), Spain (4%), Sweden (13%), UK (13%),	Operations/production manager (17%), CTO (52%), CEO (22%)

[1] Micro enterprise: >10 employees; Small enterprise: 10 – 49 employees; Medium-sized enterprise >250 employees

[2] CEO - Chief executive officer; CTO - Chief technology officer; R&D - Research and Development (designers and engineers in the areas of electronic textiles, flexible electronics, micro systems technology, and wearable computing)

The first survey mapped the range of nanomaterials for future textile applications, which are therefore relevant for prospective risk assessment. The second survey provided snapshots of the prevailing awareness of innovators regarding EHS/S risks and actions they took towards risk management.

Based on that integrative assessment, we discuss the challenges for risk assessment at an early stage of technological innovation processes. First we combine the main findings from two case studies on nano-textiles and smart textiles by applying a generic product life cycle perspective (production, use phase, end-of-life). Taking a life cycle perspective is necessary whenever uncertainty prevails regarding prospective EHS/S risks of an emerging technology. We also look into the current awareness of innovators at research institutes regarding these risks and what they do in terms of risk management under the condition of uncertainty.

4.4. Case studies

4.4.1. Case Study on Nano-textiles

Nanotechnologies involve imaging, measuring, modelling, and manipulating of matter at dimensions of roughly 1 to 100 nanometres. Engineered nanoparticles (ENP) exhibit unique physical phenomena that allow for novel technical functions. It can lead to disruptive changes in production methods and product design in a number of industrial and consumer sectors (Yu and Hang, 2011; Mangematin and Walsh, 2012). Experts envision nanotechnology to constitute an enabling technology for tomorrow’s industry and have high expectations on business opportunities (Anton et al., 2001; Nikulainen and Palmberg, 2010; Lo et al., 2012).

In the textiles sector, nanotechnologies enable the production of textiles with improved or novel functions. The use of ENP could become ubiquitous in industrial and consumer textiles in future. Current innovation projects investigate numerous properties of nano-textiles, such as self-cleaning, water- and dirt-repellent, antimicrobial, conductive and antistatic, as well as UV-absorbing, abrasion resistance, and flame protection. Moreover, nanotechnology is used to improve textile-manufacturing processes including nano-fibre spinning, fibre-processing, dyeing, and finishing (Qian, 2004; Coyle et al., 2007; Lo et al., 2007; Zhou et al., 2008).

There is also the promise that nanomaterials can boost the sustainability of production processes and applications (Fahmy and Mobarak, 2011) but evidence is rare. Nano-silver enhanced clothing, for instance, is referred to as an innovation that saves energy, water, and detergents during the use phase as the nano-silver restrains bacterial growth in textiles (Dastjerdi and Montazer, 2011). The anti-odour effect of nanosilver can help to reduce laundry frequencies, but only if consumers change their habits (wash clothing less often) (Walser et al., 2011). Therefore, some scepticism over whether the high expectations on the benefits of nano products can be realised in practice has been voiced (Fiedeler, 2008; Nikulainen and Palmberg, 2010). Exploiting the sustainability potentials of nano-textiles does not appear to be an explicit innovation target of the textile industry (Siegfried, 2007).

Comprehensive figures about the use of nanomaterials/particles in commercial products were not available at the time of the survey because manufacturers were not obliged to declare or label products that contain ENP. The table 4-2 gives an overview of the appraisal of experts regarding the use of ENP in textile products that are on the market today.

Table 4-2: Mapping of types of nanomaterials/-nanoparticles used for textile products according to the knowledge of experts in industry and academia (Som et al., 2008).

Nanoparticle material	**Number of mentioning***	**Textile application purposes**
Silver (Ag)	14/10	Anti odour effect, antibacterial textiles,
Titanium dioxide (TiO2)	13/10	UV protection, photocatalytic antibacterial and anti-dirt activity, anti odour effect, hydrophilic surface functionalisation,
Silicon dioxide (SiO2)	6/1	Hydrophobic surface functionalisation, increased wear and tear resistance, nano-encapsulation of molecules,
Carbon nanotubes (CNT)	3/2	Increased tensile strength of fibres, electrical conductive fibres, electrostatic dissipation, flame retardancy,
Fluorocarbons	2/1	Super hydrophobic surface functionalisation,
Zinc oxide (ZnO)	2/4	UV protection, anti-microbial textiles, water repellent textiles, piezo-electric energy harvesting for smart textiles
Aluminium oxide (Al2O3)	1/1	Increased elasticity and resistance to fracture of fibres
Gold (Au)	1/0	Electrical conductive fibres,
Carbon Black (CB)	1/0	Black pigment, filler additive, electrical conductive fibres,
Magnesium oxide (MgO)	0/1	Anti-microbial and anti-fungal effect, auxiliary agent, heat stability,
Layered silicate particles (nano-montmorillonite)	n.a.	UV protection, heat protection, flame retardancy, gas diffusion barrier, dye-carrier in synthetic textiles

* (industrial experts / researchers)

Concerns have been voiced over possible EHS risks of ENP that may be unintentionally liberated from products (Kessler, 2011). This can happen in various stages of the product life cycle of nano-textiles (Figure 4-1). Release of ENP is possible due to external impacts on the textile material, such as abrasion, strain, UV, water, sweat, microbes, organic and inorganic solvents, detergents, heat as well as the internal ageing of textile materials (e.g. loss of softeners). Thus far, only few assessments have been done to investigate the exposure to ENP released from products throughout their life cycle (Bello et al., 2008; Benn and Westerhoff, 2008; Vorbau, 2009; Geranio et al. 2009; Walser et al., 2011). The results of these experiments are difficult to interpret, as there is a lack of defined standards for measuring the release and the human exposure.

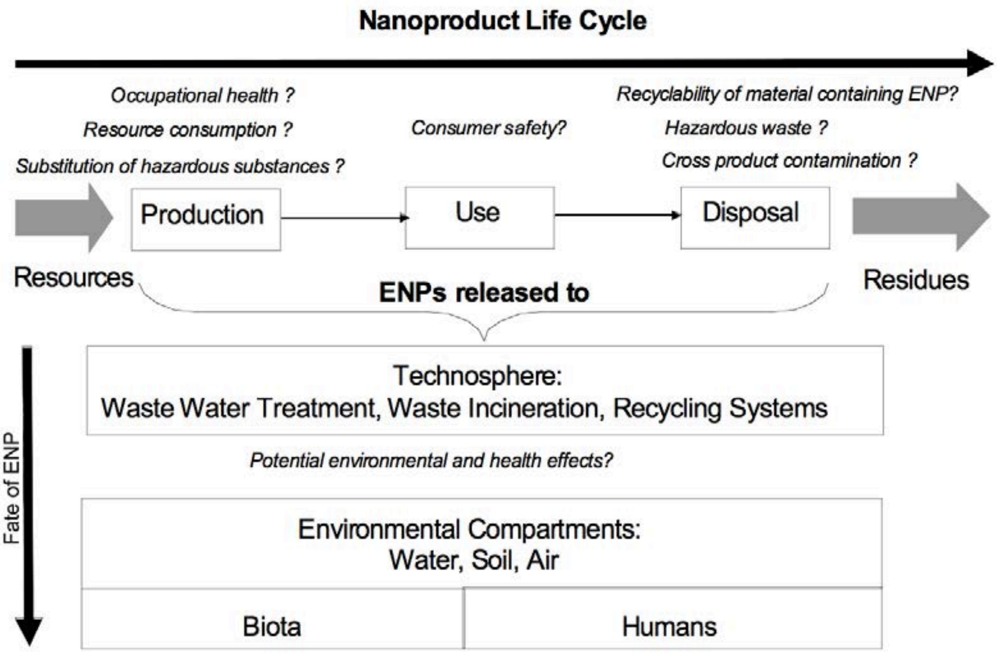

Figure 4-1: Life cycle of nano-textiles and potential impact on EHS/S

ENP are highly reactive due to the high surface area to volume ratio. Thus, free ENP probably interact easily with substances in their surroundings, such as the product matrix material and in organisms and environmental compartments. It is feared that exposure to free ENP could provoke adverse impacts on health and the environment (Gottschalk et al. 2009; Nowack and Bucheli, 2007; Krug et al. 2011). ENP are suspected to be able crossing biological barriers, such as cell membranes or the blood-brain barrier, because of their small size (Geiser et al., 2005; Elder et al., 2006; Tang et al., 2008; Wick et al., 2010). It is also believed that ENP could interact with biological structures of similar size (such as DNA and proteins) or biologically active molecules (Nel et al., 2009).

Until now, the epistemic uncertainty in regard to the EHS/S risks of ENP has not been resolved (Chaudhry et al., 2008; Stone et al., 2009; NSET & CoT, 2011; Som et al. 2011). The immense variety in properties of ENP poses a challenge for toxicological and environmental risk assessment. ENP are not uniform categories of substances in terms of particle size, shape, density, purity or surface modification. Thus, results of toxicological studies on one type of ENP cannot easily indicate the level of harm for other types of ENP, even if they consist of the same substance. The uncertainty regarding the EHS/S risks of nano-textiles also includes the fate of liberated ENP in the technical and natural environment. This is especially relevant for assessing the behaviour of ENP in the technosphere, including sewage facilities and incineration plants. An important risk factor is the design of nano-textiles and how stable the ENP are embedded in textile materials. Less stable embedded ENP can be liberated (intended or unintended) throughout the use phase or end-of-life processes resulting in human and environmental exposure. Table 4-3 provides a generalised assessment of stability factors based on findings of the case study (Som et al., 2009).

Table 4-3: Stability of the integration of engineered nanoparticles (ENP) in the textile products as a function of EHS/S risks. A higher stability is perceived to be saver because exposure to ENP is assumed to be lower.

Stability factors	Stability tends to be higher	Stability tends to be lower
Location of ENP in the fibre	ENP fully embedded in fibre	ENP fully on fibre surface or partly exposed on the surface
	ENP in core of core-sheath fibre	In sheath of core-sheath fibre
	ENP embedded in fibre	Embedded in coating
	ENP embedded in coated fibre	Embedded in uncoated fibre
Adhesion of ENP to the textile material	By covalent bonds	By dispersive adhesion[1] by hydrogen bonds
Chemical compatibility of ENP and synthetic textiles (polymers)	ENP surface is apolar	ENP surface is polar
Physical compatibility of fibre material and coating material	ENP in flexible coating	ENP in brittle coating[2]
Wear and tear properties of textile material	High abrasion resistant fibres	Low abrasion resistance
Photocatalytic active ENP [3]	No	Yes

[1] So called 'van der Waals forces' are the weaker the larger the ENP; Mechanical adhesion is relevant for large ENP (e.g. CNT),
[2] Depending of the coating thickness, thin layers (e.g. plasma coating) are more flexible than thick ones,
[3] Photocatalytic active ENP can chemically degrade the polymer matrix in which they are embedded. This can liberate the ENP.

In the case study on textile applications of ENP, we found that the assessment of EHS/S risks suffers set-back due to the following problems: First, the lack of scientific knowledge regarding ENP toxicity, mechanisms of ENP release during product life cycle, and the fate of ENP after their liberation from products. Secondly, the absence of regulation and safety standards for nano-materials makes identification, analysis and evaluation of the possible EHS/S risks difficult. In spite of the early warnings mentioned above there is little empirical basis to benchmark these risks. Thirdly, along the value chain there is a deficit of safety information about ENP contained in products or semi-finished materials that are procured from the preceding stages in the value chain. Safety data sheets often do not contain information about ENP and how to handle them safely.

While the producers of nanomaterials/-particles may know their physicochemical properties (e.g. chemical composition, size range etc.) they are usually not informed about the application purpose of the nanomaterials they sell to their customers. The actors further down in the value chain do often not have the knowledge and the experiences to deal with nanomaterials safely. Thus the employees may not be sufficiently trained and protected when manipulating nanomaterials in a manner that causes exposure to ENP (e.g. grinding nano-composite materials). Moreover, product designers have only scarce information about possible EHS/S risks of semi-finished nanomaterials, which they apply for the design of final products.

The loss of safety information from supplier to the client hinders effective risk mitigation downstream the supply chain. In consequence, the uncertainty regarding the EHS/S risks makes it difficult for textile enterprises and insurance companies to calculate the resulting enterprise risks.

There is also the fear of a backlash in consumer acceptance of nano-textiles as long as their safety cannot be demonstrated. Many innovative companies are therefore hesitant to commercialise nano-textiles.

4.4.2. Case Study on Smart Textiles

Smart materials are developed in several industrial sectors and some of them will converge in the future (Anton et al., 2001). Nanotechnology and microelectronics enable the design of highly miniaturised and unobtrusive information and communication technology (ICT). That vision is referred to as pervasive computing and foresees the seamless integration of ICT in every day objects to make them smart (Hilty et al., 2004). A fusion of textile and electronic materials will result in a new category of products: electronic textiles (Byluppala et al., 2011). These products provide augmented functionality (smartness) by means of textile-integrated electronic sensors and actuators, lightening elements, electronic devices, and power sources (e.g. batteries, solar cells) (Tang and Stylios, 2006). Smart functionality of textiles includes safety, health protection, comfort, and physiological performance inter alia. The first generation of smart textiles is close to market introduction. Clothes with incorporated electronic devices (e.g. mp3 player, solar cells) have already been commercialised (Mecheels et al., 2004). The prevailing design vision of future smart textiles encourages technology developers to pursue a deep and seamless integration of electronic and textile components. Smart textiles have the potential to become a mass application within one decade (Köhler et al., 2011; Harper, 2012).

4.4.2.1. Prospective end-of-life effects of smart-textiles and policy implications

Experiences derived from contemporary high-tech products lead to the concern that smart textiles can entail adverse side effects once they enter waste streams. The worldwide existing problem with electronic waste (e-waste) indicates that the resulting impacts on EHS/S can have a large order of magnitude (Hilty, 2005; Robinson, 2009). Massive environmental and health damage has been observed at e-waste disposal sites in numerous countries (Widmer et al., 2005). When comparing the properties of smart textiles prototypes and those of contemporary electronic products one can deduce similar EHS/S risks. Thus, smart textiles are likely to exacerbate the problems known from contemporary e-waste.

From today's perspective, the environmentally sound treatment of discarded smart textiles is not ensured because the established recycling and waste management systems are not designed to cope with this novel type of waste. E-waste recycling systems are usually organized in reverse supply chains where each operator is highly specialized on a specific task (Roman, 2012). In Europe, the take-back of discarded consumer products stands at the beginning of recycling chains. Businesses specialized in this task run collection points (turn-in system) or conduct kerbside collection (pick-up system). Take-back companies triage and merge the collected waste streams. Then, the presorted feedstock material is handed over to dismantling and recycling companies that are often organized in networks of specialized subcontractors, which apply a variety of manual and mechanical processes to separate recyclables. The various output materials (recyclables and residues) are then traded and transported to refiners - usually heavy industry companies (steel and copper smelters, waste incinerators, cement clines, etc.).

The processing of discarded smart textiles within reverse supply chains of the established recycling and waste management systems will be difficult. Existing financing schemes for e-waste recycling under the European WEEE directive do not cover this novel type of waste. Nor are the recycling technologies adjusted to it. EHS/S risks emerge due to the possible content of toxic substances (or precursors of them) within old e-textiles. A particular concern is the loss of EHS/S relevant information throughout the reverse supply chain. Information about problematic components of smart textiles (such as batteries or nano-composites) can get lost in the course of dismantling and disintegration of products. Subsequent recyclers may unintentionally co-process such components causing emissions of hazardous materials (shredding dust). This can result in occupational exposure, environmental pollution, cross product contamination, and lower quality of the recycled material. Thus, new toxic hazards can emerge during disposal processes of e-textiles and the exposure to hazards may occur in unforeseen situations (e.g. exposure to heavy metal dust during textile fibre recycling processes). It bears mentioning that we observed hardly any direct exchange of knowledge between the developers of new technologies and the recycling industry. Smart textiles designers lacked knowledge about the state of the art in recycling technology. With only a few exemptions such as the work of Hagelüken et al. (2010), the recycling businesses seem to pay little attention to the development stage of products that will end up in future waste streams.

4.4.2.2. Technology developers' awareness regarding environmental risks and end-of-life issues

A survey among 39 researchers and innovators in the smart textile sector yielded no evidence that waste prevention principles were implemented in practice (Köhler et al., 2011). Technology developers focus at improving the functional and economic performance of new products. They also pay attention to classical risk areas of product safety, such as fire safety and biocompatibility. But they pay little attention to uncertain side effects of their products, such as future end-of-life problems and the use of critical materials.

The same conclusions can be drawn from a poll among technology developers from twenty-five SMEs in the European smart textiles sector (Bakker et al., 2011). The findings suggest that a minority of the innovation-oriented SMEs has implemented environmental risk assessment frameworks in their business management (Figure 4-2). For instance, only one out of 25 companies interviewed had ever used life cycle assessment (LCA) to examine the environmental impacts of smart textiles.

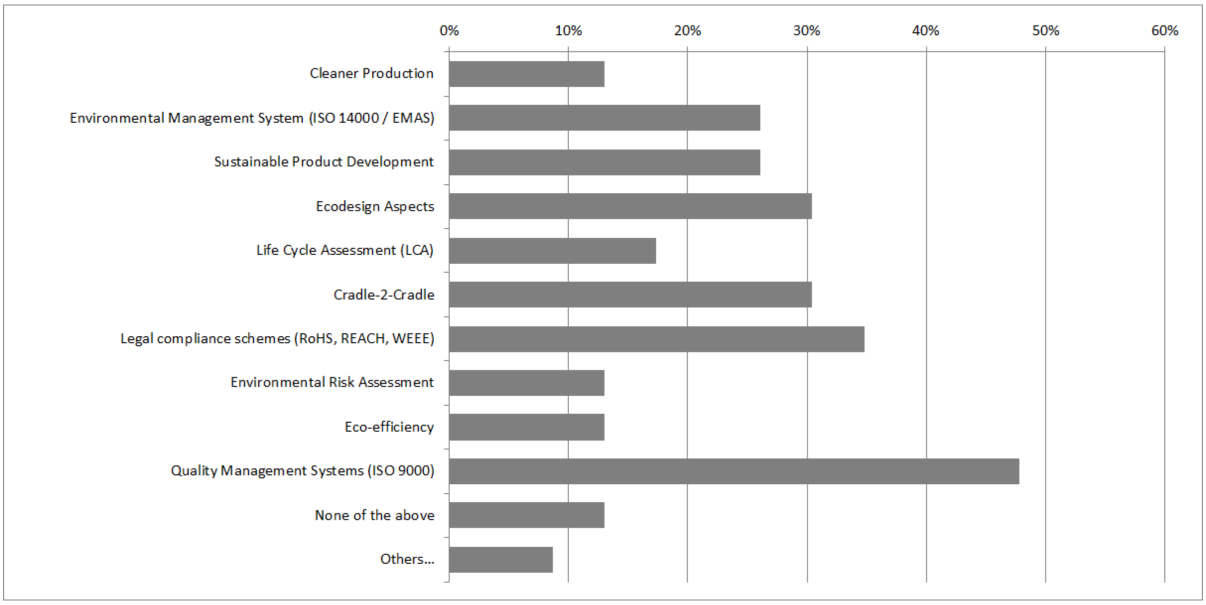

Figure 4-2: Percentage of European smart textiles companies that indicated to be familiar with respective environmental risk assessment methods. Figure adopted from (Köhler and Bakker, 2011).

While the majority of the interviewees expressed positive attitudes towards sustainable innovation and waste prevention in general terms, only a few of them could indicate what concrete measures they had taken to achieve these goals. Apparently, there are too few incentives for researchers and enterprises to strengthen waste preventative design at an early phase of technology innovation. Benefactors of research funding for smart textile innovation projects do usually not demand the implementation of waste prevention principles alongside to the development of new technologies.

Innovators of smart textiles hardly seem to be aware of the goals of European environmental and waste policies. Namely the Waste Framework Directive encourages product designers to adopt waste prevention principles. The European WEEE Directive imposes extended producer responsibility (EPR) onto the developers of new products. This form of product stewardship has the purpose to facilitate the recycling of electronic appliances. EPR can seriously influence the business strategies of innovative enterprises. The interviewees in smart textile companies revealed little awareness on the implications of EPR.

4.5. Synthesis of Results from the Case Studies

4.5.1. EHS/S risks and uncertainty

The case studies serve the identification of early warning signs on unintended side effects of nano-textiles and smart textiles. Figure 4-3 shows a generic chart of life cycle stages where EHS/S risks for future applications are identified.

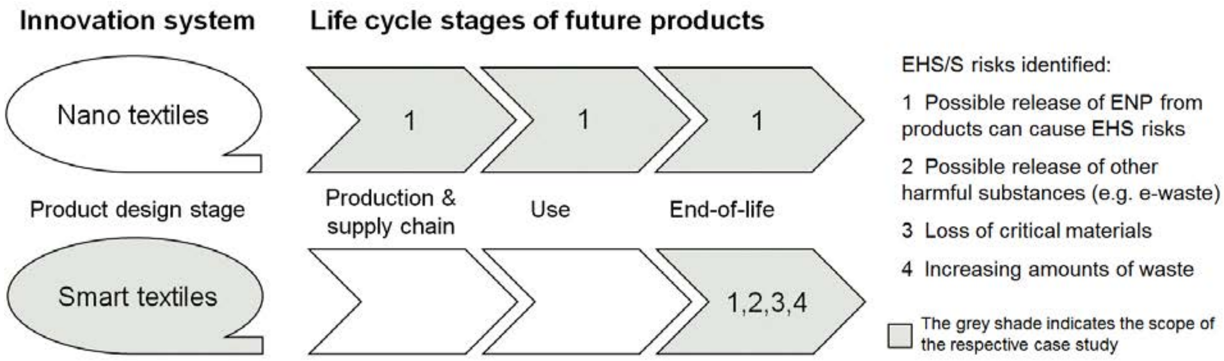

Figure 4-3: Main areas of EHS/S risks throughout a product's life cycle identified during the case studies on nano-textiles and smart textiles.

Nano-textiles represent an example of intangible EHS/S risks, which are characterised by epistemic uncertainty. The scientific knowledge is insufficient to evaluate the extent of harm caused by ENP and the magnitude of exposure to ENP. The case study on nano-textiles illustrates that nano-textiles might be safe to use as long as the ENP remain fixated in the textile matrix. The main risk source is the liberation of ENP from products as this can lead to human and environmental exposure.

The end-of-life risks of smart textiles appear more tangible since experience can be derived from the contemporary e-waste problem. The lessons learnt from e-waste give reason to expect EHS/S risks during the recycling and disposal phase. The heterogeneous inventory of substances used in high-tech products gives reason to expect new kinds of hazardous substances or their precursors in e-textiles. Disposal problems typically become visible only with a delay of a couple of years after the market introduction of new products. Moreover, the risks might be shifted towards developing countries where a large share of old textiles is shipped in order to be re-used and recycled. The uncertainty regarding the end-of life risks is mainly characterised by socio-economic aspects (market diffusion, product design details). Moreover, uncertainty prevails due to lacking exchange of relevant information that might actually exist somewhere in society or industry. This makes it difficult for smart textile developers to make informed design choices, so as to prevent end-of life risks.

We also observe that innovators tend to resort to rather simplistic ideas how to mitigate risks (an example is the frequently expressed opinion: 'yes, waste should be recycled'). However, they often fail to demonstrate the feasibility of such ideas. While most innovators perceive a general need to develop recyclable products, they tend to deem other players in the innovation system responsible to take action. In consequence, the waste problem is not addressed in the design stage but only postponed.

4.5.2. Current management practice of emerging EHS/S risks

We observe that many of those professionals who design and develop new products seem to be rather negligent of the EHS/S risks that their products may cause. In particular, smaller firms and start-up businesses consider such risks as insignificant to their core business. The case studies show that decision makers in enterprises rank the technological performance of future products and price competitiveness among their top priorities. These aspects are considered as instrumental for the market success of a company.

Usually businesses also take product safety seriously as far as they pertain liability issues. Companies manage product safety to ensure compliance with existing legislation and standards (e.g. fire retardancy standards, the EU-RoHS directive, etc.). However, regulatory frameworks do not address EHS/S risks of nanotechnology and smart textiles specifically. The lack of dedicated legislation or standards for the safety of emerging technologies makes the management EHS/S risks intangible. Firstly, due to absence of official risk reduction targets it is difficult for companies to decide which level of risk prevention is adequate and which safety measures are necessary. Secondly, the responsibility for assessing and managing EHS/S risks remains unclear at early development stages of new technologies. Under these circumstances, enterprises have little immediate competitive advantage when implementing risk prevention measures in the innovation process. The prevailing attitude is to postpone risk prevention measures until (A) more scientific knowledge regarding side effects becomes available, and (B) the legislature enacts regulation or standards imposing concrete action plans. This explains why the prevention of EHS/S risks ranks low in the priority list of technology developers.

Innovation projects in the fields of nanotechnologies and smart technologies are often commissioned without explicitly addressing risk prevention. The lack of strict risk reduction targets during the early stage of technology development creates only weak incentives for risk prevention. Funding schemes in both technology sectors do not appear to be in line with sustainable innovation and waste prevention strategies. The benefactors of national and international public innovation programs do not always require the beneficiary to assess possible side effects concurrent to the technology development. This also leads to a dissipation of responsibility for developing and implementing risk prevention strategies as mentioned above.

Beyond that, most enterprises do not proactively assess the whole product life cycle. Only one out of twenty-three SMEs of the smart textiles sector indicated to have experiences with life cycle assessment (LCA). It was also found that product developers have little knowledge about eco-design principles developed within the traditional industries (textiles, chemistry, electronics). The textile and the electronics industries, for example, have made efforts to assess the environmental impacts of products along the whole value chain. In the chemical industry, there is a broad knowledge base on environmentally sound design and engineering approaches such as green chemistry (Anastas and Warner, 2000). In the electronics industry, legal compliance with European regulation has been the driving force during the last decade. Risk reduction measures, such as lead-free soldering, were developed and implemented in the past decade. Moreover, extended producer responsibility (EPR) was imposed to electronics manufacturers by the European WEEE directive. However, the extant know-how on safe and sustainable product design seems not to be automatically picked-up by innovators in the emerging sectors of smart textiles and nano-textiles.

4.6. Discussion

4.6.1. Challenges for risk management of emerging technologies

It is hard to mitigate EHS/S risks in favour of more sustainable innovation pathways at a time when opportunities to act are best (Wardak et al., 2009). At the early stage of innovation, the knowledge about the possible side effects is limited and it is therefore difficult to select safer alternatives. Moreover, the potential risks may appear dwarfed in the light of the more tangible problems which technology developers are used to deal with.

Epistemic uncertainty about the side effects of emerging technologies is often seen as a hurdle for risk management. The implementation of risk prevention measures is often postponed until more is known about the risk, a phenomenon known as “paralysis by analysis” (EEA, 2001 p.181). Later on, if adverse side effects become evident, risk management proves often less effective because risks can only be mitigated but hardly eliminated. This situation is known as the Collingridge Dilemma (Collingridge, 1980). It describes the problems of making the right decisions under the condition of uncertainty or ignorance. Collingridge argues that strategic decisions are often made at the beginning of an innovation process, based on incomplete knowledge. Later on, the understanding of the consequences may increase. But the possibilities to influence the development trajectory of the technology decrease when the time passes by. During the later stages of a technology life cycle the variety of options wanes as society adopts to a technology (“*entrenchment*”) or becomes even dependent on a technology (socio-economic lock-in effect). Enterprises that built their business plans upon emerging technologies may be reluctant to correct an unsustainable development trajectory because redesigning the technological basis is costly (Rammel, 2003; Rip et al., 1995).

The Collingridge dilemma poses a challenge for risk management at the early stage of technology innovation processes. Collingridge suggests tackling that dilemma by maintaining as much flexibility in the development process as possible and apt to avoid lock-in effects. Moreover, technological choices that were made under condition of uncertainty must be under constant scrutiny in the light of increasing knowledge. The author points out that factors, increasing the social costs of wrong development trajectories, must be identified and avoided from the very beginning. This is particularly important for technology development in a competitive environment.

The precautionary principle can serve as a framework of orientation as long as uncertainty about adverse side effects of new technologies prevails. However, Gollier and Treich (2003) point out that precautionary risk management policies must lead “reduce the degree of irreversibility for future choices” in order to “biases decisions in favour of more flexibility”. Implementing life cycle thinking in the innovation process can help anticipating the environmental and safety relevant aspects of new technologies. The due consideration of the prospective context of production, use, and disposal of future products yields useful information for a precautionary risk management. Thereby, sustainable design heuristics can be used as a risk management mechanism. Figure 4-4 illustrates how the implementation of eco-design principles at the fuzzy front end of a new product development process can help to preserve a good design freedom. Design principles, derived from previous innovation cycles, offer guidance for the save development of new technologies. Eco-design can be an element of precautionary risk management. Although such heuristics cannot address unprecedented risk aspects of emerging technologies they nevertheless provide a wealth of product related context information, setting a useful system boundary for forward-looking risk mitigation in the innovation process.

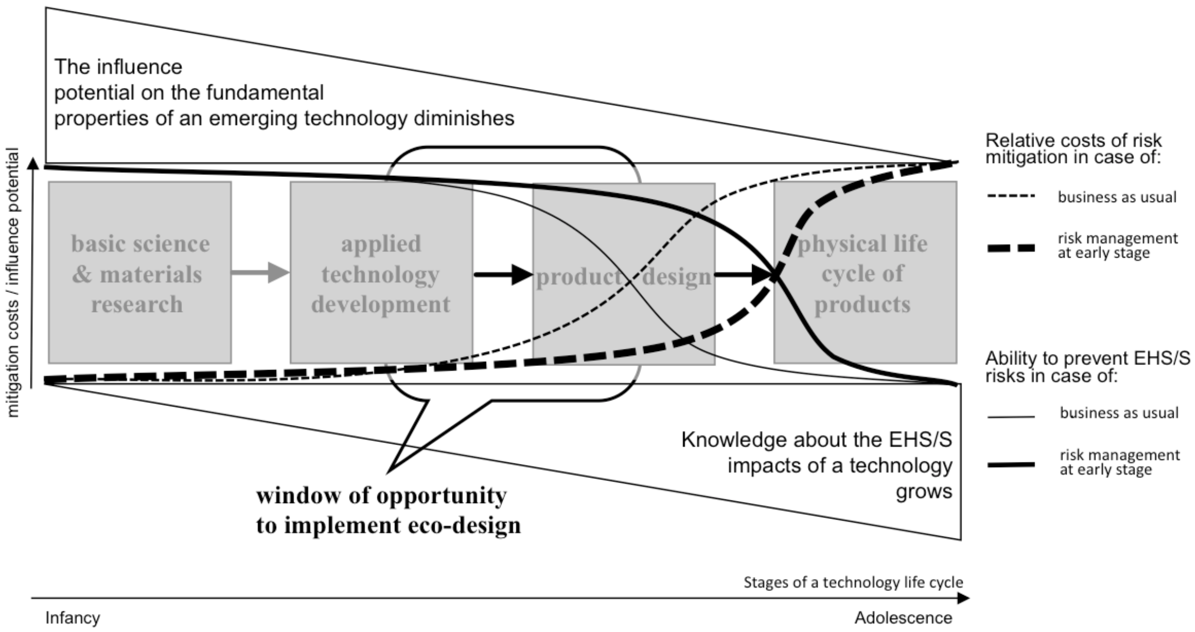

Figure 4-4: The intended effects of risk management (e.g. eco-design) at the early stage of technology development. Light charts symbolise increasing risk mitigation costs (dotted line) due to entrenchment occurring during the product design process. Risk preventative measures (bold charts) can delay the entrenchment and preserve some ability to avoid side effects.

4.6.2. Strategies for managing risks during the early innovation phase

How can enterprises harness business opportunities of emerging technologies while preventing intangible EHS/S risks? Uncertainty should not be reason to neglect risks. Numerous approaches to precautionary risk management under uncertainty have been suggested in literature (e.g. Collingridge, 1980; EEA, 2001; Cameron and Raman, 2005; Ehrenfeld, 2008; Hull, 2010; Höck et al., 2011). It is key to implement risk prevention measures early in the technology development process. From the perspective of businesses however, the precautionary principle seems to be not easily applicable. Entrepreneurs and technology developers prefer more concrete guidelines. A few possible starting points of risk preventative innovation strategies are outlined below.

(1) The implementation and further development of eco-design principles

Companies may pick the low hanging fruits first, that is, start implementation of established methods for sustainable product development. By doing so, they can also train their skills in analysing the emerging risks within their own technology sector. Innovators can become more receptive for early warnings on intangible risks if they seek interdisciplinary knowledge co-operation with risk researchers and sustainability experts.

Pioneers in sustainable design have noted that new products should always be developed with having the full product life cycle in mind. Possible EHS/S effects of products often occur dislocated and with delay (e.g. health and environmental hazards can arise from waste disposed of in unsanitary landfills). That phenomenon is known as risk migration. Established risk assessment methods, such as FMEA and SWOT, should therefore be complemented with life cycle thinking. The scope of failure effect evaluation must be extended beyond the sole analysis of product functionality. A tailored life-cycle analysis (LCA) helps identifying the environmental impacts of technologies on the background system. Current innovations in the arena of LCA address methodological simplification so that life-cycle assessment becomes readily applicable for practitioners in small businesses (Bakker et al., 2011). Smart textile developers, for instance, can engage by making life cycle inventory information available to open-source LCA databases. The increased availability of LCA data on smart textiles will help to make the environmental aspects more tangible and thus better manageable.

Design for Environment (DfE) provides assistance for technology designers to reduce life-cycle-wide environmental risks. Thus far, eco-design principles have mostly been applied to commoditised technologies. However, technological and socio-economic entrenchment renders environmental improvements difficult once that products have proliferated on the mass-market. Redesign of fully developed products is usually a costly task and can reduce a companies' expected return on R&D investments (Rip, 1995; Rammel, 2003). Therefore it is wise to implement eco-design principles right at the start of product innovation (Figure 4-4). Eco-design principles and assessment methods specifically addressing the environmental risks of electronic consumer products have been developed e.g. by Stevels (2007).

The toxicological effects of many ENP will remain uncertain in the immediate future. Thus, minimizing the exposure to ENP is a good strategy to reduce EHS/S risks. Appropriate design of nano-textiles may prevent the release of ENP during the product life cycle. ENP and nanostructured materials may hold potentials for the substitution of hazardous substances and for reduced material consumption. These potentials should be evaluated and exploited whenever possible. However, innovators must beware of risk migration effects and avoid shifting hazards to other product life cycle stages. Therefore, it is important to investigate the whole life cycle of products produced with embedded ENP. For the substitution of hazardous substances, engineers' understanding of the potential hazardousness of ENP has to be improved. Based on our findings in the case study on nano-textiles we propose to consider the following precautionary measures in order to minimize EHS/S risks (Som et al. 2009):

- During the production phase, it is recommended to generate ENP in situ or at least to bind ENP powder in liquid or solid agents. In this way, the exposure to airborne ENP can be reduced in order to protect workers.
- It is valuable to check for ENP-free alternatives in order to reduce consumer exposure to ENP during the use phase of nano-textiles. The ALARP principle ("as low as reasonably practicable") (Cameron and Raman, 2005) can be adopted to minimise the risk of exposure to ENP.
- Chemical functionalisation of ENP makes it possible to link the ENP to the textile material permanently. In addition to consumer safety, these measures are also likely to increase the quality and long-term functional performance of the nano-textiles. Thus, consumer safety can go hand in hand with high product quality.
- In order to prevent recycling and disposal problems of nano-textiles the product designers should make sure that ENP are not liberated when the textile materials disintegrate (e.g. in shredding processes).

In the nanotechnology sector, there are also voluntary stewardship initiatives and voluntary reporting schemes that provide industry with expertise to address nano-specific EHS/S risks (Hoeck et al. 2011; van Duuren-Stuurman 2012; Nanosafer 2011; NanoSafe2 2008; Hull 2010). Additionally, the EU framework program 7 and national agencies founded numerous projects that investigate the (eco)toxicological hazards and apply life cycle assessment to emerging nano-products. Furthermore, the Swiss textile federation founded a guideline for the sustainable development of nano-textiles (TVS 2011).

(2) Governance of technology development processes

This can push innovation trajectories onto more sustainable pathways. Public research programs are key drivers for innovation in nano-technologies and smart technologies. Public research programs often mention the need for sustainable technology development. Thus, policies for sustainable innovation and waste prevention have to be implemented explicitly within such funding schemes.

It is recommended that research-funding schemes, such as EU FP7 and successors, impose clear incentives to the beneficiary to assess prospective EHS/S risks concurrent to the technology development. Innovators should demonstrate not only the technical and economical feasibility of a new technology but also the safety for human health, the environment, and sustainability. For instance, the systematic investigation of EHS/S risks, including LCA, should be made a compulsory requirement of new technology development under public funding schemes. Furthermore, tenders for public funded R&D should also require the implementation of concrete waste prevention and recycling principles. This corresponds with the urgent need to reduce the risk of depleting critical raw material. Stimulating research on design principles that phase-out the use of scarce elements from mass products can be seen as a key approach of precautionary risk management.

Research institutes and industry have also a societal responsibility to exploit the sustainability potential of emerging technologies such as reducing resource consumption, reducing the generation of waste and substituting hazardous substances. They could commence voluntary stewardship strategies to find sustainable technology trajectories.

(3) Clear regulatory frameworks or standards

They are required to make the management of EHS/S risks in emerging technologies feasible. Risk reduction targets are instrumental for implementation of risk prevention measures in the technology development process. Sending clear signals to industry is seen as an essential policy instrument for sustainable innovation. For example, legislated policies such as the European RoHS/WEEE Directives constitute strong drivers for progress in green electronics. It appears recommendable to enterprises to adopt a waste preventative innovation strategy early in technology development in order to prepare for changes in the regulatory framework. Enterprises, which are proactive in eco-design can benefit from strict regulation as it can create competitive advantage. Voluntary stewardship policies are a precautionary response to regulatory uncertainty. For example, enterprises can establish integrated product policy (IPP) or adopt eco-label compliance schemes.

In the case of nanotechnology the responsibility for safe handling of ENP lies with industry and trade. Suppliers at every stage of the value chain of nanomaterials should provide their customers with appropriate safety datasheets and advise for safe handling. Moreover, information about potentially hazardous components in products should be preserved until the end-of-life processing. Producers of final nano-products and smart textiles should make EHS/S relevant information available their consumers and recycling businesses by means of product labelling or online product safety databases.

Regulatory activities have begun to evolve. For example, the Swiss agency for health has proposed a precautionary matrix for products and applications using engineered nanomaterials. This precautionary matrix may help industry and trade to identify possible sources of risk in the production, use and disposal of engineered nanomaterials (Höck et al, 2010).

4.7. Conclusions

Our case studies illustrate that smart- and nano-textiles can entail risks for the environment, human health & safety, and sustainability (EHS/S). The integration of nanoparticles (ENP) or electronic components in textile products may result in adverse side effects during the life cycle of future products. The EHS/S risks are intangible due to the epistemic uncertainty regarding the mechanisms of exposure and the extent of possible harm. The magnitude of risks depends on product design, circumstances of use, and the destination of products at the end of their useful lives.

The discussion of lessons learnt from adverse side effects of existing technologies leads us to the conclusion that EHS/S risks can materialise as enterprise risks in the long run. Businesses may miss the objectives of their innovation projects due to the societal response to unmanaged EHS/S risks. They can trigger a backlash in customer acceptance, stakeholder criticism, and tightened regulation.

The assessment of potential EHS/S risks during the technology development process supports enterprises and research institutes in risk preventative decision-making. In spite of initial insufficient levels of knowledge it is possible to recognise the EHS/S risks concurrent to the genesis of new technology generations. Paying attention to early warnings can guide precautionary risk management. Approaches of risk preventative technology development also include life cycle thinking, eco-design, and innovation governance. Implementation of these measures should not be postponed until more knowledge about EHS/S risks becomes available.

Innovation strategies that meet the expectations of stakeholders (consumers, legislature, etc.), regarding safety and eco-performance, have a lower risk of misguided investments. The preventative management of risks EHS/S can gain benefits in the long run as it can help reducing liability costs. Moreover, safer and more sustainable products provide for better customer acceptance. To that end, innovative companies will gain a competitive advantage in the market.

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CHAPTER 5

Challenges for eco-design of emerging technologies: the case of electronic textiles

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5.1. Introduction

Electronic textiles (e-textiles) are a novel type of high-tech products resulting from the integration of electronics and technical textiles or clothing. The aim to augment the functionality of textile products, to make them "smart". Smartness is understood as the intrinsic capability of a product to interact actively with its surroundings and respond to external stimuli [1]. The development of this emerging technology necessitates new design approaches cutting across traditional industrial boundaries [2]. Contemporary focal points of e-textiles innovation are the selection, testing, and adoption of enabling technologies, such as electrically conducive fibres and interconnections and their integration in textile materials. Examples of textile integrated electronic components are fibre-based electrodes (sensors and actuators), woven, embroidered, or printed logic circuits, flexible lighting elements, components for power generation and storage (e.g. flexible solar cells, batteries) and many more [3, 4].

E-textiles provide exciting prospects for innovation. But on the flip side, they may entail adverse environmental impacts. One particular area of concern is the disposal of e-textiles after the end of their useful product life. It appears likely that e-textiles may cause recycling and disposal problems if they are designed and mass produced without heeding their end-of-life fate [5]. There are similarities between the properties of e-textiles and contemporary electronic products, with the latter causing global environmental and social problems due to the vast amounts of electronic waste (e-waste) arising [6, 7]. E-waste usually contains a variety of harmful substances or their precursors, which can cause damage to human health and the environment. Moreover, e-waste contains non-renewable materials, such as precious metals and rare earth elements, which leave a large environmental footprint even before they are incorporated in products. The contemporary problems around e-waste have led to the recognition that electronic high-tech products should be designed in a way to prevent adverse impacts in the end-of-life stage. Waste prevention by design is a far more auspicious strategy than end-of-life treatment and recycling [8].

The most decisive opportunity to influence the environmental performance of a new technology exists at the early stage of the innovation processes [9]. Luttropp and Lagerstedt emphasise that, at the conceptual stage, designers hold the key for sustainable product development.

[30] Parts of the article were moved to chapter 1 (sections 1.2.3 & 1.5.1.1 & 1.5.1.2).

Industrial designers and engineers have substantial influence on the life-cycle-wide environmental performance of the products they conceptualise [10-12]. Not only the physical properties of a product are determined by its design but also the ways in which it is produced, used and disposed of [13]. However, it has been observed that companies tend to negate environmental aspects during the conceptual phase of product design processes [14]. At later design stages, the possible solutions are often limited to mere fixtures rather than radical improvements of a new product's eco-performance [ibid]. Therefore, the life-cycle-wide environmental aspects should not be overlooked during the design and development process of e-textiles.

A conceptual framework for the sustainable development of products is known as eco-design, or Design for Environment (DfE) respectively [15]. It offers a toolbox of principles that support environmentally conscious choices in the product development process [16]. Design for Recycling (DfR) is a subset of eco-design that specifically aims at the optimisation of products for repair, refurbishment, and recovery of materials at the end of their life cycle. In a wider sense, DfR aims at extending a product's lifetime in order to prevent waste and to preserve non-renewable resources. Eco-design approaches have been developed by various industrial sectors [17, 18]. The electronics sector, for instance, has developed a spectrum of cleaner production concepts commonly referred to as 'Green Electronics' [19]. Industrial approaches towards applied eco-design of electronic products have been extensively researched and published [20]. Stevels stresses the importance of creating 'Ecovalue' (defined as the ratio of ownership costs to the environmental burden of a product) rather than eco-efficiency [ibid. p29]. What really matters for eco-design is creating a high consumer value with products that have a low eco-burden.

This paper discusses strategies for environmentally conscious design of e-textiles focussing on waste prevention. After a mapping of contemporary innovations in e-textiles, their expected properties are appraised with a view to possible future end-of-life impacts. Existing eco-design guidelines of the electronics and textile sectors are reviewed as a basis for the discussion of eco-design strategies for e-textiles. The objective of the paper is putting forth ideas how the development of this emerging technology could be adjusted to sustainable trajectories right at the early stage of innovation.

5.2 Study set up

This research was spurred by the participation in a three-day focus group colloquium in May 2011 (Future Textiles Expert Summit) [21]. Forty-five international experts from textile industry, design consultancies, and academia created visions of future innovations in e-textiles. A growing focus on environmental impacts, energy and resources saving, and recycling was identified as a mega-trend influencing the innovation process of e-textiles. The colloquium concluded that "*we will need to invent new materials, e.g. organic or recyclable" to create socially, environmentally, and economically viable products. Technological innovations need to be translated into "business models with sustainability as a main driver*" [ibid p19].

This triggered further research on how e-textiles can be designed with regard to a sustainable end-of-life treatment. The results presented in this article summarise findings from an iterative research process including desk research as well as communications with the community of e-textile developers. It started with a broad review of literature and online sources about contemporary innovations in the field of e-textiles. Further, the body of knowledge on DfR approaches in the electronics and textile sectors was reviewed. Then, the feasibility of existing DfR principles was evaluated against the expected properties of e-textiles. The findings of this desk research were presented to design professionals, business executives, and stakeholders in the area of e-textiles. Thirteen designers and companies, interested in the issue, were invited to a two-days workshop at which they discussed DfR ideas for e-textiles [22]. The modality of the workshop was 'design inclusive research' [23]. The participants formed small groups and experimented DfR through hands-on design experiments. For this purpose, they were given a design challenge (design and prototype a wearable activity monitor with particular attention to longevity and recyclability). Each group debated their ideas with other groups and implemented them in form of artefacts. After the workshop, photographs of these artefacts were shown to experts from textile recycling businesses and their appraisal about potential recycling issues was noted. Subsequently, a panel of six design-engineering scholars consolidated and substantiated the DfR ideas and derived eco-design strategies for e-textiles.

5.3. About e-textiles

The current innovation process in the smart textiles sector could counteract the goals of environmental and waste policies. Taking into account contemporary examples of e-textiles, it can be expected that existing schemes for take-back and recycling of e-waste or old textiles are not designed to process such a feedstock. The following section (5.3.1.) reviews current innovation trends in e-textiles and section 5.3.2. provides an overview of possible problems if e-textiles were to enter the existing recycling and disposal system.

5.3.1. Contemporary innovation trends

E-textiles can be seen as a forerunner of smart technologies that are thought to permeate our daily lives in future. These products are described as "*fashionable technology*" in which novel and advanced functionality is combined with a sense for fashion and aesthetics [24]. Wearable computing denotes a far-reaching vision of computing devices being unobtrusively embedded into garments [25]. Researchers and enterprises from both, the electronic and the textile sector, pursue the development of e-textiles. That endeavour can be interpreted as convergent technological innovation (Figure 5-1) as materials and devices from distinct domains of technology are amalgamated in the same product.

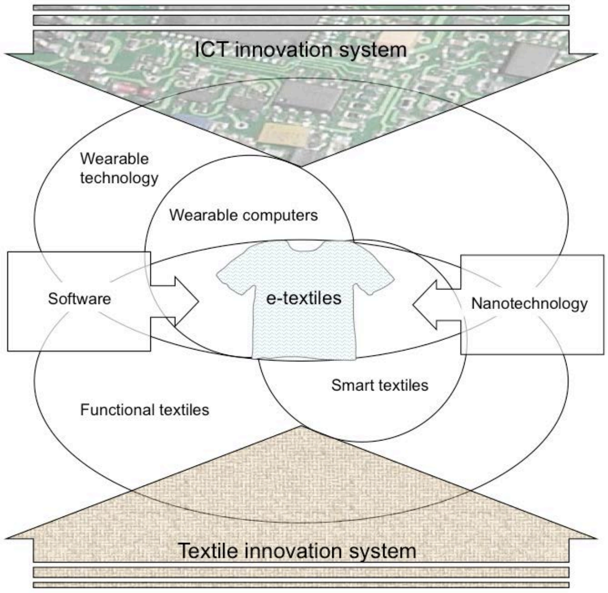

Figure 5-1: E-textiles in the converging innovation system of the textiles and electronics sectors. (adopted from Köhler, 2008).

The convergence of textiles and electronics necessitates new design concepts in terms of materials composition and configuration of components. Textile integrated electronics necessitates attributes such as flexible, stretchable, and foldable. E-textiles must, for their users to accept them, become comfortable, fashionable, and washable while retaining their smart functionality over many use-cycles. Successful realization of e-textiles therefore necessitates new design and configuration paradigms as well as new materials and technologies. An interdisciplinary community of designers, crafters, and fashion artists pioneers the development of e-textiles as they handcraft textile-electronic components and make their concepts openly accessible via instructables, blogs, websites, and workshops [26]. Handcrafting and knowledge sharing activates creativity to experiment with new techniques and to conceive smart functions. A variety of enabling technologies does already exist but they need to be further developed so as to match with the consumer expectations. There is a broad spectrum of future applications in the development pipeline entailing a fusion of functions or materials from electronics and textiles. As an illustration of the variety of engineered materials used in smart textiles the following paragraphs provide a snapshoot of contemporary innovations in the field.

<u>Electrically conductive fibres and yarns, contacting and bonding elements, and electronically active textile-materials:</u>

Schwarz et al. report the development and testing of electro-conductive yarns consisting of a textile core yarn (e.g. polyester) enwrapped which silver, copper and stainless steel filaments or coated with chemically deposited gold layers [27, 28]. Marozas et al. evaluate the properties of silver-plated nylon electrodes to be used as textile sensors for wearable electrocardiogram monitors [29]. Bedeloglu et al. present the development of fibre-shaped photovoltaic cells consisting of polypropylene fibres that are coated with thin layers of PEDOT (conductive anode), photoactive materials (a conjugated polymer composite with C61 carbon nanoparticles) and a transparent metallic nano-layers consisting of lithium fluoride/aluminium [30].

Flexible circuit boards embroidered, woven, or printed on fabric.

Weremczuk et al. describe an ink-jet printing technique by which a humidity sensor can be printed directly on fabric using silver-nanoparticle ink [31]. Zeagler et al. present techniques to create e-textile interfaces, such as an embroidered jog wheel and a tilt sensor [32]. A new method for adhesive fixation of circuits on textile substrate is reported by Linz et al. The authors conclude that it is a candidate technology for future mass production of e-textiles [33]. Perner-Wilson et al. give account on handcrafting techniques to build modules (e.g. a crochet potentiometer, felted pressure sensor, knit stretch sensor), which can be used as personalized textile-based human-computer interfaces [34].

Conductive and semi-conductive polymer foils and fibres, polymer-based electronics, and nanotechnology.

Knittel et al. describe the preparation of conductive fabric for electrical heating applications based on the in-situ polymerisation of PEDOT (an electrically conductive polymer) on cotton and synthetic fabrics [35]. Organic electro-chemical transistors were created on natural fabric by Mattana et al. who coated cotton with gold nanoparticles and thin-film PEDOT layers. The authors conclude that the technology "*paves the way for a future complete integration between electronics and textiles*" [36].

The examples above illustrate the heterogeneity of high-tech materials and technologies that are expected to find their ways into textile products. By now, a variety of semi-finished e-textiles materials, such as conductive yarns, inks, adhesives, and manufacturing techniques are available commercially. Developers frequently utilise off-the-shelf components when creating e-textile applications [37]. Though clothes incorporating electronic devices (e.g. mp3 player, solar cells) have already been put on the market they failed commercial break-through as yet. However, the technology bears the potential for future mass-application [38-39]. Hot spots of innovation in e-textiles are the market segments of consumer garments, health care, work wear, and military. E-textiles are expected to unlock interesting grow rates for the apparel industry in future [40].

5.3.2. Expected end-of-life impacts of e-textiles

High-tech products usually turn to waste because they are replaced by newer models after a relatively short service life - a phenomenon known as progressive obsolescence [41]. E-textiles in form of consumer applications are subject to this kind of obsolescence in that they combine short-lived electronics with the fleeting fashion trends that govern the apparel market. The findings of a technology assessment study suggest that old e-textiles will emerge as a new category of waste soon after their introduction on the consumer mass markets [42]. These mobile products could also lead to increasing consumption of batteries, which need to be disposed of when exhausted. In that, they resemble the contemporary e-waste problem. But discarded e-textiles also pose new issues that result from their unique properties. In particular, the dispersion of electronic materials within large amounts of textile waste will make it difficult to recover valuable materials from a low-grade feedstock [43]. Potentially hazardous substances (or their precursors) are also dispersed and therefore hard to separate for safe disposal. From today's perspective environmentally benign management of waste e-textiles is not guaranteed for the following reasons:

(1) Large mass flows of waste e-textiles can be expected if e-textiles experience breakthrough on mass markets [5]. E-waste problems typically emerge with a delay of a few years after market introduction of new EEE.
(2) Landfilled or incinerated e-textiles can cause health and environmental risks, such as emissions of hazardous substances. Occupational health risks can also emerge when e-textiles undergo recycling processes.
(3) Textile-embedded electronic components contain small amounts of scarce materials, such as silver, gold, and rare earth elements, which are scattered across large textile surface areas and hard to recover.

It appears hardly feasible to process such blended feedstock by means of existing recycling facilities. Recovering minute amounts of valuable materials from a large mass flow of textile bulk materials is technically and economically difficult. Without recycling, there exists a risk that mass application of e-textiles accelerates the depletion of scarce resources, such as technology metals and resources for fibre production (agricultural land, fertilisers, irrigation water etc.).

5.4. Implementation of eco-design in the innovation process of e-textiles

5.4.1. Challenges for eco-design of e-textiles

The developers of e-textiles strive for a seamless integration of electronics in textiles but exact properties of e-textiles remain intangible as long as the technology is not fully wrought. This makes it difficult to anticipate the prospective end-of-life problems and to derive waste preventative design recommendations. Most of the existing eco-design solutions from the electronics or the textiles sectors are impractical because they do not match with the expected properties of e-textiles. For instance, the DfR recommendation to use of snap-fit fasteners (instead of screws) for plastic enclosures of electronic devices is pointless if they are sewed or embroidered on fabrics [70]. It will also be hard to design electronic components for easy disassembly in a traditional way if they are to be laminated onto fabric. The use of metal-coated yarns for e-textiles conflicts with the DfR principle to limit the use of plastics parts with surface metallisation. That means, new design solutions need to be developed alongside the innovation process of e-textiles.

The tables 5-1 to 5-4 show a selection of eco-design principles from the electronics sector, which are related to waste prevention and end-of-life treatment. They were adopted from the ECMA-standard 341 [54], the Green Electronics Council [69], and other scholarly authors [46]. The eco-design principles were evaluated against the prevailing design visions of e-textiles developers. The evaluation indicates opportunities (+) and challenges (!) for eco-design. The former term is understood as the possible environmental benefit that could be gained by taking advantage of favourable properties of textiles and smart materials. Challenges, on the other hand, are understood as a call for development of new eco-design solutions in cases in which the properties of e-textiles mismatch or collide with existing eco-design principles.

Table 5-1: Challenges and opportunities for eco-design referring to material efficiency.

Eco-design principle	Evaluation	Discussion
Reduce the diversity of materials in the product	!	The amalgamation of electronic and textile components increases the variety of materials found in a product.
	+	The use of conjugated polymers (conductive or semi-conductive plastics) can reduce the amount of metallic components. Innovations in organic electronics can stimulate the design of e-textiles free of metals and silicon.
Reduce the weight of the product	+	Trend towards flexible thin-layer electronic components can pave the way for to weight savings and increased resource efficiency,
	+	Lightweight textile materials can replace solids (plastic, metals) as casing or backing material in devices,
	!	Increasing number of devices used per person can outweigh savings.
Using renewable materials	+	Natural fibres (e.g. cotton, hemp, kenaf, bamboo) can replace plastics as casing or backing material. This helps in reducing the consumption of fossil resources and lowers the carbon footprint of products.
Using recycled materials	+	Textile materials can, by virtue of their flexibility, be easier refurbished or remanufactured into new products than those rigid materials typically found in electronics.

* Opportunity (+); Challenge (!)

Table 5-2: Challenges and opportunities for eco-design referring to hazardous substances.

Eco-design principle	Evaluation	Discussion
Avoid use of materials that cause adverse environmental impact (Depollution)	+	Classical hazardous substances were banned by the RoHS directive (e.g. lead) or may become obsolete due to technological change.
	!	Use of new materials with uncertain environmental risks (e.g. nanoparticle).
	!	Risk of cross-contamination during recycling.
Provide information to end-users and recyclers about parts requiring special handling	!	Seamless integration and unobtrusiveness of textile-integrated electronics make it unlikely that end-users will be aware of them when they discard the old product. End-users may not be able to undertake source separation of waste. Textile recyclers may lack information about hazardous components.

Batteries should be easily identifiable / removable	!	Seamless integration of small and flexible batteries may cause difficulties in removing them. This could complicate textile recycling processes.

* Opportunity (+); Challenge (!)

Table 5-3: Challenges and opportunities for eco-design referring to product obsolescence.

Eco-design principle	Evaluation	Discussion
Timeless design	!	The apparel market is subject to rapidly changing design trends and renders textile products unfashionable at seasonal intervals.
	+	Smart textile materials may offer possibilities to adjust design features to new fashion trends (colours, shape, thickness) without replacing the product.
Easy to upgrade and repair	!	Fault detection and maintenance are difficult due to seamless integration of electronic components. Repair may damage reusable garments.
	!	Difficult to update wearable computing devices with regard to firmware, data formats, networking protocols, data safety requirements. Software obsolescence obstructs the availability of servicing information needed to preserve smart functions for a long use phase.
	+	Higher fault tolerance due to networked and redundant architecture of textile embedded electronics.
Understandable design for the user	!	The design trends of unobtrusiveness and seamless integration of e-textile components obstruct the user’s comprehension of the product
Use of standardized parts (power supplies, batteries, connectors)	!	Standardisation of e-textiles components is lagging behind technological innovation and rapidly changing fashion trends.
	!	Standardisation is a complex task due to the vast heterogeneity of the converging technology and its parent industrial sectors (textile, electronics).
Allowing for the reuse and replacement of common parts or modules of the product	!	Difficulties to replace electronic components being tightly integrated in textiles. In particular, this concerns textile-embedded batteries.
	!	The trend towards low-cost components reduces economic incentives for reuse. User habits in regard to apparel products may discourage reuse.
Reuse/refurbishment of old products	!	The export of old e-textiles to foreign second-hand clothing markets (as part of charity of commercial trade of old garments) could conflict with legislation (The Basel Convention) because of waste electronics contained in them.

* Opportunity (+); Challenge (!)

Table 5-4: Challenges and opportunities for eco-design referring to end-of-life treatment.

Eco-design principle	**Evaluation**	**Discussion**
Easy recycling of materials	!	Dissipative resource loss can be expected due to the scattering of electronic materials within large amounts of textile carrier materials
Easy and safe separation of parts containing hazardous substances	!	Electronic components are highly dispersed within old textiles. Identification and separation of such parts will pose problems.
	+	Opportunity to avoid use of hazardous substances in the first place.
Easy separation of parts intended for different end of life treatment	!	Reuse and recycling of old garments will have to deal with seamlessly integrated electronic components. Separation of electronic parts may damage reusable clothes.
Easy disassembly of parts	!	Parts that are sewed, embroidered or laminated cannot be freed easily.
	!	Textile fibres may jam apparatus for mechanical disassembly of e-waste.
Limit the number of polymers used in the product	!	Contradiction to the trend towards use of polymer electronics, nano-composites and their integration into synthetic textiles.
	+	Substitution of metals and semiconductors with polymers.
Avoid coatings and surface finishes on plastic parts	!	Flexible thin-film electronics is based on coating technology. Fibre coating (metallization) or printing constituted an enabling technology of e-textiles.
Using biodegradable materials	+	Natural fibres (e.g. cotton, hemp, kenaf, bamboo) are biodegradable and can replace non-renewable plastics as casing or backing material

* Opportunity (+); Challenge (!)

The systematic evaluation of existing DfR rules leads to the conclusion that the technological convergence necessitates an overhaul of such guidelines. Not only the combination of materials and functions of textiles and electronics renders the existing eco-design approaches impractical. Equally relevant is the fusion of two types of products that used to have totally different use-cycles and end-of-life destinations. This could accelerate the obsolescence of e-textiles, leading to larger amounts of waste. Waste preventative eco-design strategies for e-textiles must therefore adopt a life-cycle perspective, e.g. by taking the reasons into account that could encourage the consumers to use them for a longer time. The following section presents eco-design strategies that were distilled from the results of the ‘design inclusive research’ workshop with smart textile developers.

5.5. Eco-design strategies for longevity and recyclability of e-textiles

5.5.1. Harnessing the inherent environmental advantages of innovative materials

Sustainable design concepts for e-textiles should prioritise waste prevention over recycling. Designers should search for possibilities to prolong the useful life of e-textiles, holding off their obsolescence. This could be achieved by designing products for repair, refurbishment and re-use. The couture sector has brought about examples of upcycling old garments into new fashionable and value-added goods [71]. These experiences can inspire the design of high-tech apparel to be future vintage clothing rather than waste. Smart materials and technologies can be deployed to make products reconfigurable in that they adjust their looks if fashion changes. This would help in delaying obsolescence and prevent waste. Design for upcycling of e-textiles implies that faulty electronic components can be replaced without damaging the fabric. Printing technology could allow to print-over faulty organic electronic components easily. In future, such technologies may render classical approaches of repair and refurbishment (e.g. resoldering) obsolete. The environmentally conscious application of advanced technologies and materials can expedite the innovation process in sectors such as polymer electronics.

There are opportunities to reduce the consumption of primary resources by using recycled fibres and to avoid the use of hazardous substances. Textile materials can replace problematic components in electronic products (e.g. replacing plastic in enclosures of devices with textiles). The use of miniaturised ICT-devices can pave a way to reduced resource consumption if small devices replace the functions of larger ones. Moreover, opportunities exist for decreasing the consumption of scarce metals if polymer electronics replace silicon-based electronics. Minimizing the consumption of batteries and electricity during the use phase is equally important. Textile technology offers opportunities to design out contemporary problems in end-of-life treatment. For instance, eco-friendly textile materials may substitute for traditional materials in the housing and packaging of devices (such as aluminium, plastics). Typical textile accessory parts, such as push-buttons, velcro strips, or sewed-in pouches can be used to mount electronics on textiles in DfR friendly ways (aiming at minimising the disassembly time).

Bio-inspired design concepts, based on smart materials, can bring about many desired functions without the use of electronic components [72]. Singh et al. review several biomimetic design concepts of smart textiles, such as self-healing fabric and tear or wrinkle resistance. Self-healing nano-materials enable the creation of self-repairing products that are less prone to wear and tear. Materials with switchable properties offer new possibilities for designing recyclable artefacts as they make possible self-disassembly techniques [73]. Stimuli-responsive polymers could be used to make destructible yarns or adhesives that decay under exposure to heat, microwaves, or magnetic fields [74]. For instance, organic thin-layer circuits could be printed on textile surfaces using a smart resin binder that dissolves upon exposure to microwaves. Such technologies, if installed in automated recycling facilities, could be capable of dismantling large amounts of discarded post-consumer e-textiles cost efficiently.

5.5.2. Compatibility standards

Certain e-textiles components may become subject of progressive obsolescence quicker than others, for instance batteries and chargers. If these peripherals are not designed for compatibility from the very beginning then the users will need to replace them with each new version of e-textiles. This problem is well known from the mobile phone sector and has contributed much to the increasing amount of e-waste. Observers have noted that some manufacturers (OEM) deliberate incompatible chargers as a means of planned obsolescence [80]. Another aspect that has to be kept in mind is that smart textiles are envisioned to play a role in ubiquitous computing. Smart objects can suffer from progressive obsolescence affecting the inbuilt software and data protocols of smart objects. Increasing incompatibility in relation to the quickly evolving ICT environment turns aged products to waste because users have difficulties to operate them in a state-of-the-art ICT environment.

Compatibility standards offer a chance to avoid these pitfalls as they have a coordinating function. Standardisation reduces unnecessary and undesired variety and helps to avoid the formation of ungovernable path dependencies. Without compatibility standards being established concurrent to the innovation process, proprietary quasi standards may emerge and become entrenched as the owners grow due to market success. This can result in lock-in effects, as these companies are reluctant to redesign their products. Hence, the standardisation process should be commenced before the innovation process enters the commercialisation stage. Egyedi and Muto analyse the effects of compatibility standards on the sustainability of ICT and conclude that it has beneficial effects regarding longevity of devices and their peripherals [82]. Moreover, compatibility standards were found to facilitate repair and refurbishment as they provide for easier availability of spare parts. They argue that "*standardization can thus become a green strategy*" at sector level [ibid p. 9].

The designers of e-textiles can further the development of standards. The European Committee for Standardization (CEN) has published a technical report on smart textiles, which notes that "*compatibility and interoperability of these parts will be an important aspect*" [1]. Table 5-5 provides an overview of components of e-textiles that are relevant candidates for compatibility standards.

Table 5-5: Components of e-textiles that are relevant for compatibility standards.

Functional aspects of e-textiles	Design features to be standardised
Batteries, chargers, external power supplies	Geometrical design of connectors and layout of pin arrays should follow the 'one-fits-all' principle, Voltage levels should match commoditised batteries,
Connectors, plugs, interface parts	Geometrical design and logic design of plugs and pin arrays
RF antennas (data networking, power transmission)	Emerging textile applications should be developed in compliance to existing standards (e.g. ISO/IEC 18000 (for item management), EPC global (Electronic Product Code), Qi (wireless charging)),

Parts that are prone to attrition (e.g. sensor pads with skin contact)	Design aspects regarding fixtures, connectors etc. Open source documentation of design specifications,
Peripherals (e.g. memory cards or their future equivalents)	Upward compatibility to wider ICT systems ensures that long-lived e-textiles remain operable when external systems change (receive and read data, or execute code),
Firmware, drivers, and software (‘Apps’)	Interoperability (= multi-platform plurality), compatibility of components with embedded software,
Data communication protocols, file formats, data encryption protocols,	Open source model for software that work in connection with external devices of e-textiles. Open file formats for exchange of content information (e.g. data gathered by textile embedded sensors).

Existing standards should be adopted in the development of new textile-based technologies for e-textiles. One example is the use of the micro-USB plug for mobile phone chargers, which could be used for e-textile chargers as well. New standards or amendments of existing ones should be developed for e-textile components that deviate from existing standards in regard to their unique properties (e.g. softness, flexibility). An example of a new interface standard is the proprietary Qi standard for wireless charging [83]. It could become relevant for charging e-textiles without physical connectors. However, proprietary standards bear the risk of vendor lock-in effects. Open standards in contrast, are created in an open procedure (everybody can contribute the further development of specifications) and the specifications for hardware or data-formats are available to implementers on basis of an ‘open-source’ licence [84]. One big advantage of open standards is community support. Krechmer explains that open standards “*are supported until user interest ceases rather than when implementer interest declines*” [ibid]. This is a vital precondition to avert progressive obsolescence. The LilyPad Arduino is an example of an open developer platform for e-textiles, which is based on an open-source concept [85]. Open-source development models, such as the Open Source Hardware (OSHW) principle [86], encourage the crowd of developers to collaborate and share product design and implementation details. The open source concept can support compatibility of different product generations (mitigate the design-freeze of aged products to avoid virtual wear-out). The public availability of data can facilitate repair and upcycling as a means to combat obsolescence of old e-textiles.

5.5.3. Labelling

Old e-textiles might end up in recycling facilities for post-consumer textiles. The electronic components in e-textiles are thought to disturb mechanical fibre reclamation processes and can potentially contaminate the output material. E-textiles must therefore be separated step before they enter purified fibre fractions that are destined for fibre-to-fibre recycling. It is important for recycling operators to recognise e-textiles among thousands of conventional clothing items within seconds. The unobtrusive integration of electronics in e-textiles poses a challenge for the triage step of a post consumer textile recycling line.

An e-textiles label could ease the recognition of e-textiles within a large flow of old clothes. Such a label should consist of a unique logo that can be recognised on the fly. Preferably, a visual logo should be combined with a machine readable tag in order to support automated recycling processes. A machine-readable tag can convey additional data, such as an Electronic Product Code (EPC), which provide the recycling operator with repair instructions and material specifications via a web-hosted database. The use of textile or printed RFID tags would be one option. However, the RFID would introduce additional electronic components into textiles. Moreover, privacy concerns have been voiced against the RFID-tagging of consumer products. Quick Response (QR) codes are a versatile alternative to RFID. Kuusk et al reported the integration of embroidered QR codes for augmented reality applications [87]. QR codes can be made with textile production methods (e.g. embroidery, printing). The scanning of QR codes does not require expensive equipment (a web-cam is sufficient) and can be implemented easily in the sorting lines of existing facilities for old textiles recycling.

5.6. Conclusions

Possible risks, such as the dispersion of valuable materials within difficult-to-recycle waste streams, should be counteracted before e-textiles pervade the mass market. The biggest challenge might be to encourage life-cycle thinking at the conceptual stage of technology development. Experiences in the electronic sector suggest that the environmental performance of a whole technology generation is determined by choices taken at the early stage of innovation. Unsustainable design choices at the beginning can lead to path dependencies that are referred to as “entrenchment” of development pathways [88]. Networked ICT products have a particular disposition for this kind of “lock-in” effects, [81]. Users become quickly dependent on the new functions of products once that they have proliferated at the market. This can result in socio-economically irreversible consumption patterns that entrench undesired side effects on the environment (such as e-waste problems) [89, 90]. Thus, e-textile developers should strive to avoid “lock-in” effects by making them interoperable. It is recommended to establish open compatibility standards for e-textiles concurrent to the development of consumer products.

The ongoing innovation process opens a window of opportunity to create e-textiles in a more sustainable manner. Eco-design can help in preventing future end-of-life problems of this converging technology. A solution for some of the known waste problems with high-tech products may present itself in form of advanced materials, such as printed polymer electronics. However, the inherent environmental advantages of certain new technologies are unlikely to materialise just by serendipity. They must be proactively searched for. Harnessing the possible benefits of emerging technologies requires a dedicated innovation strategy for the sustainable development of e-textiles. This article has undertaken a first scoping of possible eco-design approaches that could help in achieving this goal.

Extant eco-design principles (such as design for recycling (DfR)) can be adopted from the electronics and the textiles sector but they must be further developed so as to fit with the specific properties of e-textiles. It is advisable to constantly scrutinise the potential of eco-design solutions to solve problems in time. How realistic is the application of certain innovative technologies under market conditions and when will they become available? It must be taken into account that it can take many years to accomplish market readiness of enabling technologies, such as fibre-shaped electronics and nano-technology. This can hamper the adoption of advanced eco-design ideas if they rely on smart materials. Moreover, the properties of contemporary prototypes are likely to differ from those of commoditised products in the future. The shift of manufacturing technology from crafting at lab-scale to production at industry scale causes substantial design changes. E-textiles designers ought to keep this in mind so as to avoid environmentally conscious design choices to fall overboard later on. Although many decisions on fundamental product properties and functions are made at the early stage of the design process they can be subject to economic or aesthetic reconsideration at the stage of production design. Hence, the feasibility of eco-design solutions should be monitored throughout the whole product development process.

Likewise, the practicability of DfR concepts should be evaluated in discourse with recycling experts. The recycling industry too needs time to adopt, test and adjust innovative end-of-life concepts to make them competitive. Less sophisticated DfR approaches might prevail over high-tech solutions if they are quicker to implement. Hence, a waste preventative innovation strategy necessitates co-ordination between developers of e-textiles and the recycling industry.

A big challenge is implementing life cycle thinking at the conceptual stage of technology development. This is necessary because the environmental performance of products may depend on seemingly minor design aspects that are easily overlooked in the beginning. One example is the content of critical materials in certain high-tech components. The availability of scarce elements (e.g. rare earth elements) may not be a major concern in the design stage. But the industrial supply with critical raw materials might become tight once e-textiles, which may contain such elements, are up-scaled for mass production [47]. Early warnings about emerging problems ought to be considered already at the early design stage when fundamental decisions are taken about the technical concepts and functional features of future e-textiles.

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Chapter 6.

Conceptual Approach for Life Cycle Assessment of smart textiles

Adopted from: LCA-to-go (Köhler and Bakker, 2011; Köhler, Bakker, v.d. Velden, 2011)

6.1. Introduction

From a life cycle perspective, the environmental footprint of a company is often dominated by the impacts of the products rather than the impacts of manufacturing processes. Enterprises, whose business is designing and creating new products, can thus improve their environmental footprint by making environmentally conscious decision in the course of new product developments. This requires a good understanding of the life-cycle wide environmental aspects of products. Companies are therefore increasingly motivated to implement Life Cycle Assessment (LCA) to make life cycle perspective operational in the business management context (UNEP, 2009).

The LCA method allows for a comprehensive evaluation of product-related impacts on environmental safeguard subjects. The life cycle perspective offers an analytical framework, which is also known as cradle-to-grave analysis. On this basis, it is possible to compare the accumulated environmental impacts of products to alternative design solutions thereof (Horne et al. 2009). Thereby, the notion of 'product' encompasses goods and services as well as, in cases of product systems, auxiliary components that are necessary for providing functions (ISO 14062) (ISO, 2002). A truncated variant of LCA, the so-called cradle-to-gate analysis, only takes the production and manufacturing processes into account. The methodological framework of LCA is specified by the non-binding international standards ISO 14040 and ISO 14044 (ISO, 2006a; ISO, 2006b).

While there are no legally binding requirements for businesses to conduct LCA, more and more companies evaluate the environmental impacts of their products on a discretionary basis. In this regard, LCA differs from statutory instruments, such as Environmental Impact Assessment (EIA) or Strategic Environmental Assessment (SEA), which are stipulated by legislation such as the instance European directives (EC, 1985) and (EC, 2001). These instruments are an obligatory part of planning procedures for large industrial development projects, public infrastructure plans (Finnveden and Moberg, 2005). In contrast, LCA is applied as a discretionary decision support instrument. LCA is applicable in the context of the following goal situations (EC, 2010):

- Meso/macro-level decision support: strategic planning, policy making, and governance,
- Micro-level decision support: design and planning of products, facilities and processes,
- Accounting: monitoring the environmental performance of products, sectors, or countries.

In regard to strategic decisions, LCA is often applied in combination with other impact assessment methods. For instance, it can supplement SEA in municipal planning procedures if actor-specific aspects are to be compared (Björklund, 2012). In the framework of EIA, the system approach of LCA can support the comparison of process alternatives or abatement choices in regard to their "*indirect effects*" (Tukker, 2000). The scope of LCA differs from EIA in that it includes non site-specific environmental aspects (de Haes, 1993). They encompass the materials and energy inputs as well as the emissions along the whole value chain of products (JRC, 2012). Such indirect processes can occur far away from the present location of the object of investigation but they can entail global environmental impacts nevertheless. In this respect, the life-cycle perspective helps to avoid shifting environmental problems beyond a site-specific system boundary (Guinée, 2002).

Decision support at the micro-level is the most relevant application area of LCA in industry. It is mainly used by firms in the context of environmentally conscious product development processes (eco-design) and in the framework of environmental management (e.g. cleaner production, green procurement) (Cooper and Fava, 2006; Kloepffer, 2008). The UNEP states, "*Life Cycle Assessment is a tool for the systematic evaluation of the environmental aspects of a product or service system through all stages of its life cycle*" (UNEP, 2009). LCA supports environmentally conscious decision making in the course of future product development. It is intended to be "*a useful tool for identifying potential problems before they arise*" (ETBPP, 2000). Making environmentally conscious choices in the design process necessitates taking the whole life cycle into account. It must be kept in mind that eco-design should not result in shifting environmental problems from one stage of the product life cycle to another. The application of LCA can help to understand and prevent undesired side effects of products. LCA provides answers to the question which product design variant performs best in regard to environmental impacts during the use-phase and at the end of their use life.

Accounting applications of LCA in industry refer to monitoring and controlling the results of decisions taken in the context of product design and in corporate management processes. LCA provides a metric for environmental performance measuring that makes the effects of decisions visible and transparent. It serves as a standardised instrument for environmental reporting and green marketing to substantiate claims about environmental improvements. In this regard, LCA is a cornerstone of environmental product declarations (EPD).

Over the past two decades, much effort has been committed on the sophistication of LCA in order to make the method both, scientifically rigour and applicable in practice (Zamagni et al. 2012). The methodological advancements and the international standardisation as well have led LCA to become the most powerful decision support tool for environmentally prudent product design. By now, LCA is widely accepted as a scientifically grounded quantitative environmental analysis method. However, there are still barriers to the implementation of LCA as a regular business procedure, particularly in small and medium sized enterprises (SME) (Knight and Jenkins, 2009). Conducting a full LCA that is conform to the standard ISO 14040 is a time-consuming and costly exercise (ETBPP, 2000). Scharnhorst notes that, “*being a holistic tool makes LCA difficult and requires highly sophisticated skills by the practitioner to handle and adjust the method*” (Scharnhorst, 2008).

The methodological complexity of LCA limits its usefulness as a decision support instrument for businesses. Practitioners often face difficulties to comprehend peculiar methodological aspects of LCA, such as scope, functional unit, system boundary, and allocation, and to use these concepts appropriately. This is particular difficult for multifunctional high-tech products, which are produced in multi-staged value chains. A meta-analysis of twelve LCAs on printers for the consumer market found that each study was based on different assumptions and definitions (Bousquin et al. 2012). This heterogeneity makes it hard to compare different LCA and to derive common conclusions. In business practice, decision makers often perceive the results of LCA inconclusive because they depend on the assumptions taken for the analysis (system boundary, functional units, etc. (Brandao et al. 2012).

A particular problem is the application of LCA at the early stage of the innovation process leading to the development of novel products. Thus far, LCAs on emerging technologies, such as smart textiles, are rare. The main difficulty is the lack of information concerning aspects of future developments, such as the exact properties of future products and the circumstances of their use. Moreover, uncertainty exists in regard to future product life cycles (i.e. how and where these products will be produced, transported, and for how long, how often, under which conditions they will be used). The uncertainty necessitates making assumptions or even guesses, which leads to a very low quality of input data. Conversely, attempting a more accurate LCA means waiting for more robust data to become available in the course of product commoditisation. This would postpone the implementation of LCA as an environmental decision support instrument. Under these circumstances, it is likely to miss opportunities for eco-design of emerging technology.

To avoid this kind of “*paralysis-by-analysis*” at the early stage of the development of emerging technologies a different approach to LCA is necessary. LCA should be applied concurrent with the innovation process because it can help product developers to make environmentally conscious design choices. For this reason it is important to overcome the prevailing barriers so as to make LCA a feasible decision support tool for SME: The practicability of LCA for decision makers in SMEs should be improved. Zamagni et al. (2012) recognise a research need for integrated approaches that support the application of LCA. They conducted a research gap analysis on LCA and found that there is a demand for improvements in three aspects of LCA:

(1) “*reducing the number of environmental impact indicators,*
(2) *intervening at the level of methodological choices in the inventory phase, and*
(3) *working on data availability*” (ibid. p.S45).

In regard to strategy (1), Vogtländer et al. (2001) developed the Eco-costs / Value Ratio (EVR) as a ‘fast-track’ approach to LCA. The prevention-oriented Eco-costs concept takes the monetary value of the environmental burden of products into account. The Eco-costs method generates a single indicator that is easily apprehensible for product developers and business decision makers since the results are expresses in Euro. The '*fast-track*' LCA approach is designed to be used in the specific decision context situation of the product design process (Vogtländer, 2009). Jansen and Stevels (2007) developed a benchmarking method for the environmental product assessment (EPAss) of existing electronic consumer goods. It uses a reduced set of fact sheets for the benchmarking of energy, embodiment, and end-of-life aspects. The method yields information about the feasibility and benefits of 'green' re-design options. In regard to strategy (3), the availability of data LCI data is facilitated by IDEMAT, a freely available database of about 1500 materials, processes and components that are common in the field of industrial design-engineering (Vogtländer, 2012).

Zamagni et al. (2012) name further possibilities for the simplification of LCA:

- "*simpler interfaces and less time-consuming models,*"
- "*methods and software tailored to specific industrial sectors.*" (ibid. p.S45)

These challenges are addressed in this chapter through the development of a sector-specific LCA approach for smart textiles. The aim is facilitating progress beyond the state of the art in LCA-application in an emerging technology sector at the early stage of innovations.

6.2. Objectives and framework of research

It matters to provide innovators at SMEs with an environmental decision support tool in order to guide the technology development process towards sustainable trajectories. This is to be achieved by lowering the prevailing barriers for LCA-application in companies that develop smart textiles in form of commodity products. The following research question guided the research described in this chapter:

<u>Research question 1:</u> What is the status quo of environmentally conscious decision-making in the development process of smart textile at SMEs?

<u>Research question 2:</u> How can progress be made beyond the status quo regarding LCA application at the early stage of innovations in the smart textiles sector?

The research was carried out in the framework of the European Union Seventh Framework Programme (FP7/2007- 2013) "LCA-to-go". The overall intention of the LCA-to-go project was boosting the application of LCA in small and medium sized enterprises (SMEs) (LCA-to-go, 2013). The project had three main objectives:

1: Facilitating a "break-through" regarding LCA use in SMEs.
2: Development of customized LCA approaches for each sector[31].
3: Development of sector-specific concepts for eco-design and LCA tools.
4: Development of an open source LCA toolbox for free online application[32].

[31] Next to smart textiles, the LCA-to-go project addressed the following target sectors: Bio-based plastics; Industrial Machines; Electronics; Renewable energy; and Sensors. These target sectors were chosen as they represent major constituents of the European economy. Moreover, they are of very high relevancy in terms of environmental impacts and environmental improvement potential.

[32] This objective of the LCA-to-go project was outside of the scope of this PhD research since it is implemented by other partners of the LCA-to-go project consortium.

The project thereby pursued a needs-driven approach that pays foremost attention to the application purposes of LCA in business practice of SME. The guiding idea behind the needs-driven approach was the innovators' perception that – in practice – right decisions can often be made based on approximate knowledge. That means, simplified LCA results can already point at the most relevant environmental aspects with moderately accuracy, which offers sufficient decision support at the early stage of product design. This approach has the potential to make LCA more feasible in this decision context situation as it saves a big share of efforts that have usually to be invested for undertaking rigour LCA. Hence, the LCA-to-go approach, presented here, follows the doctrine to reduce the methodological complexity of LCA. The aim is providing innovators and product designers as smart textile SMEs with a simplified LCA-based instrument that delivers results in less that one hour. This was considered a precondition for the applicability of LCA in 'real world' enterprises.

Smart textiles are an example of an emerging technology that is still at an infant stage of product commoditisation. The innovation process in the smart textiles sector offers opportunities to prevent future environmental problems, such as increasing consumption of energy and critical materials as well as disposal problems. Among the target sectors of the LCA-to-go project, smart textiles were chosen as this sector represents the early stage of product innovation as a specific LCA decision context situation.

6.3. Study setup

The development of a methodological concept for a simplified LCA-to-go was structured in consecutive tasks during a 2011 and 2012 as follows:

1. Review of the status quo of LCA implementation in the smart textiles sector — Section 6.4.
2. Survey of SMEs in the smart textiles sector regarding LCA needs — Section 6.5.
3. Case study on LCA application in an applied product redesign process in a SME — Section 6.6.
4. Methodological concept development — Section 6.7.

Task 1 encompassed a broad review of literature about the status quo of LCA implementation in the smart textiles sector. The literature sources included scientific literature databases, reports of previous research projects (as far as publicly available), conference presentations & papers, company publications, and other forms of communication via the Internet. The literature base was screened for existing LCA in the smart textile sector (none was found). Due to the lack of smart textile specific LCA, five environmental assessment studies on products that come close to smart textiles in some regard, were examined. The following aspects were analysed: scope/objective, the applied methodology, the system boundary, and main results. Then, the literature review was extended to LCA-related research projects in the classical textile sector. Further, the normative frameworks (regulations, standards) of the textile and the electronics sectors were considered to find out in which way they could have implications on LCA of smart textiles. Finally, a review of existing LCA tools that are freely available to

SMEs via the Internet was undertaken. This analysis was implemented in conjunction to task 3, which served as a practice-oriented evaluation environment for the usability of these tools.

Task 2: The needs of SMEs regarding LCA were investigated through questionnaire-based remote inquiries and questionnaire-guided phone interviews.

Task 3: An applied LCA on a smart textile product was carried out in cooperation with one SME that develops and commercialises a smart sensing floor system for ambient assisted living. The study setting was design inclusive research, that is the LCA was integrated in a design project at the SME, leading to an environmentally informed redesign project on the sensing floor system. The case study served as the test bed for exploring the viability of LCA in the context of a SME.

In task 4, the findings, generated by the foregoing research, were analysed in the light of LCA theory. Then, the results were then generalized (taking synergies to other case studies into account) and the conceptual proposal for the sectoral LCA-to-go tool was adjusted to these findings. The advantage of adopting the aforementioned procedure was twofold: scientific validity of the research is maintained and practical relevance for SMEs was enhanced. A validation of the proposed methodological concept is scheduled within the LCA-to-go project, including implementation and testing of the tool in ten smart textiles SME. However, the results of the implementation and testing phase are not reported in this work because the timeframe of the LCA-to-go project extends the PhD research period.

6.4. Literature review

6.4.1. Status quo and future perspectives of LCA application in the smart textile sector

6.4.1.1. Review of LCA studies on smart textiles

Extensive review of scientific literature databases and browsing literature available via the Internet did not yield information regarding life cycle assessments of smart textiles or similar technologies such as electronic textiles, wearable computers, ambient intelligence etc. Thus far, the smart textiles sector has hardly implemented LCA in practice. There was also no indication of companies or research institutes currently undertaking LCA on smart textiles. Previous investigation on end-of-life implications of electronic textiles already indicated that environmental aspects are not regularly assessed during the development process of smart textiles at research labs and science organisations.

In personal communication however, some industry representatives indicated that a few companies did evaluate the environmental impacts of smart textiles. Such assessments were undertaken for internal decision support without disclosing results to the public. It was therefore not possible to review existing LCA studies on smart textiles and to derive experiences on methodological aspects. As a remedy, environmental assessments (EA)[33] of products were

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[33] Not all studies reviewed were fulfilling the methodological requirements of ISO 14040 conform LCA. Nevertheless, the environmental assessments (EA) were informative for the detection of the status quo in LCA application in the textile sector.

reviewed that have partly similar characteristics as smart textiles. The review included the following environmental assessment (EA) studies:

- EA1: LCA and eco-design of an electrically operating plush toy (Teddy bear) (Muñoz et al. 2009). Here, the plush toy is considered here as a proxy to a smart textile product although it is, strictly spoken, not a smart textile as it lacks seamless integration of electronics in textiles.
- EA2: Prospective Environmental Life Cycle Assessment of Nanosilver T-shirts (Walser, 2011). The study compares the prospective environmental impacts of nanotechnology enhanced textile products before their mass commercialisation.
- EA3: Environmental assessment of six textile products and almost 500 unit processes from cradle to grave in the lifecycle of textiles (Laursen, 2007).
- EA4: Two LCA cradle-to-grave LCAs of 2 wireless personal electronic products (heart rate monitor and weather station) (Winco, 2009). The LCA was considered as a showcase for small and 'mobile' products that have similar functions as smart textiles may provide in a wearable configuration (integrated in clothing).
- EA5: LCAs of inkjet-printed RFID antenna (Kanth, 2011) and (Kunnari et al. 2009). The studies were taken into consideration because the inkjet-printing technology is expected to become a relevant mass-production technology for textile electronics in future.

From the reviewed EA-studies it can be inferred that the environmental assessment of smart textiles should focus at the power consumption during the use phase (clothing care) as well as the materials needed to produce them. LCA on electronics lead to the assumption that power consumption or batteries are dominant environmental aspects during the use phase. Table 6-1 summarises the relevant aspects that are addressed by the reviewed EA studies.

Table 6-1: Summary of relevant environmental aspects identified in environmental assessment studies (EA)

Relevant aspect	**Environmental assessments (EA)**
Energy	**EA1:** Production of batteries **EA2**: High energy demand of plasma technology **EA4:** consumption of batteries dominates
Materials	**EA1:** Electronic components (PWB) have highest impact **EA2**: Nano-AG consumption seems insignificant **EA4:** Toxic emissions in raw material processing for battery production **EA5:** PWB have 95% higher resource consumption than ink-jet printed electronics (5%).
Production phase	**EA2:** Plasma technology has high impacts **EA3:** Floor covering: Fibre manufacturing is dominating in all categories. Clothing: Toxic emissions in fibre manufacturing. **EA4:** Batteries production causes 90% of the total energy consumption and emissions
Use phase	**EA1:** Consumption of batteries dominates **EA2:** Substantial energy saving potential during use phase, depending on user habits. Opportunities of technical properties (nano-AG) can fail if users

	don’t change habits. **EA3:** Clothing: washing, drying, ironing is dominant environmental aspect.
Disposal phase	**EA1:** disposal phase appears to be the least important **EA2:** toxic releases during use and disposal are of minor relevance. **EA5**: printed RFID antennas cause lower hazardous emissions than PWB antennas
Uncertainty	General problem of lacking data, restricted access to data due to non-disclosure policies.

It is important to mention that all but one of the reviewed LCA studies exclude the context of product use from the system boundary. Because of the early stage of innovations, there are little experiences about the complete life cycles of smart textile products. However, the use context can have substantial influence on the environmental assessment of smart textiles due to indirect aspects of their advanced functions (smartness). The analysis of these indirect effects requires information about the use context, which is very case specific. For instance smart workwear is intended to boost productivity of workers by increasing their mobility, flexibility and abilities to communicate with remote technical systems. Another example concerns smart flooring technology that can be used to monitor/control the energy consumption of buildings, making the facilities capable of responding to actual user needs in real time.

And finally, from the ICT sector it is known that sophisticated computing products can influence the environmental performance of their users (e.g. due to dematerialisation and due to making communication, travel, or work processes more efficient). Moreover, ICT products with higher functionality have the potential to substantially influence environmental performance of other systems in technosphere, depending on the whole use context (see chapter 2). Thus, the advanced functionality of smart textiles, notably their “smartness”, adds an additional dimension to the environmental assessment.

6.4.1.2. LCA application in the traditional textile and apparel sector

In the mature textile sector, publicly funded research projects dedicated to LCA were implemented in the past (COST Action 628) and the present (PROSUITE). Recently, various LCA studies on synthetic fibres (Advansa, 2011) cotton fibres (Levi Strauss & Co., 2008) and modified cellulose fibres (Shen and Patel, 2010) were commissioned by different large textile companies and carried out at public research bodies and consultancies.

These gate-to-gate LCA studies tend to focus at the production steps within the textile value chain since textile corporations are increasingly interested in implementing cleaner production mechanism and reduction of carbon footprint / process water usage. LCAs that include the use phase of the textile life cycle (including laundry, drying, ironing) were conducted with focus at the environmental performance of detergents and washing machines.

Several cradle-to-gate LCA studies on clothing have been undertaken by fashion retailers (e.g. M&S) or branch organisations of the textile industry in the UK (Collins and Aumônier, 2002). Patagonia assessed the fibre-to-fibre recycling of old polyester textiles by means of LCA

(Patagonia Inc., 2005). Though not all of these studies have been made available to the public in detail, these initiatives demonstrate the growing sense of responsibility for environmental impacts among corporations in the textile sector. For the most part, bigger players on the apparel market (fashion brands and large textile producers) have undertaken efforts in LCA. The outdoor fashion industry has teamed up and launched a beta-version of the "*The Eco Index*" (Outdoor Industry Association, 2012), an LCA-based environmental assessment tool designed to provide companies with intelligence on the improvement potential of their products.

No LCAs, created by textile SMEs could be found during the literature review. Textile SMEs seem to be less active in undertaking LCA than large apparel brands and multinational textile companies. However, this does not necessarily indicate that SMEs are altogether desinterested in environmental assessment. Rather, this might be caused due to SMEs' having a pragmatic approach to LCA as an internal decision support tool rather than for external communication. National branch associations of the textile sector offer LCA support to their members, including development and dissemination of customized LCA tools for textile SME. For example, MODINT, the Dutch trade association of the fashion, interior design, carpets and textiles industry, has commissioned the development of such a tool (Modint, 2012). It is now offered to textile companies in the Netherlands.

In conclusion, it can be said that for the textile and apparel sector there are some branch specific LCA tools available– some of these are online tools accessible for members or subscribers. These tools differ in the level of sophistication and not all of them are strictly compliant to ISO 14040 (serving rather as quick-check tools). Made-by.org for instance, offers a scorecard approach for social and environmental aspects of fashion products (MADE-BY, 2012).

6.4.1.3. Review of freely available LCA Software for SME

In preparation of the LCA-to-go tool development the state-of-the-art in existing free LCA software tools was evaluated. The evaluation encompassed eight LCA tools, which come into question to be used by SMEs. These LCA tools are freely available online and promise easy applicability for practitioners. The following LCA tools were evaluated:

- Eco-cost database (www.ecocostvalue.com)
- eVerdEE (www.ecosmes.net)
- Limas (http://www.limas-eup.eu/)
- Life cycle analyses (http://design-4-sustainability.com/life_cycle_analyses)
- Nike Design Tool (http://www.nikebiz.com/Default.aspx)
- EIOLCA (http://www.eiolca.net/)
- Ecolizer 2.0 (http://www.ovam.be/jahia/Jahia/pid/2230)
- Ccalc (http://www.ccalc.org.uk/)
- OpenLCA (http://www.openlca.org/)

In addition, two LCA and eco-design support tools of the established textile industry were reviewed. Nine freely online-available LCA tools that come into question to be typically used by SMEs were tested out. The evaluation served the exploration of the state-of-the-art of available LCA software tools.

These proprietary tools were developed by branch associations and textile industry and specialized for their specific needs. Each tool was evaluated against the following criteria[34]:

1. **Straightforwardness:** How much time does it take, to create a LCA? Is it possible to generate a simple LCA within 2 to 3 hours? Does the tool guide a non-skilled LCA practitioner easily through the different steps of a LCA (e.g. define goal, scope, functional unit, etc.)?
2. **Graphical User Interface (GUI):** How intuitive is the GUI? Does it work platform independently (different operation systems and web browsers (Safari 5, Chrome 18, Firefox 12, IE 9))? How self-explaining are the different data input and output forms?
3. **Novice user friendliness:** Can the tool be applied without knowing anything about LCA? Does it offer an understandable help function?
4. **LCI Database:** Does the tool give access to a database of secondary LCI data? Is the information significant for the typical use case? Is the database structured in a way that materials and processes can easily be found? How old is the information in the database? Is the database continuously maintained and updated?
5. **Users group:** Whom is the tool intended for?
6. **Export features:** Can results be exported easily?
7. **Indicators:** What indicators are used to display results?
8. **Use of result:** What is the intended application of the LCA results?
9. **Unique feature:** Does the tool offer innovative feature that go beyond the state of the art in free LCA tools?

The results of the evaluation suggest that the current state-of-the-art of LCA tools suffers various shortcomings, which make their use unsatisfactory for SMEs (Table 6-2). Most of the extant free LCA tools are not usable in an intuitive manner for novice LCA user at a SME. The novice LCA user is hardly able to operate them without lengthy preparation. Only a few tools are applicable without previous training or lengthy study of software manuals. It usually takes much effort to register as a new user, to learn to handle software and to find the way through the various software menus and input/output screens. Moreover, the tools also offer little (if any) assistance for non-LCA experts to interpret the LCA results and to translate them into eco-design guidance. Most tools offer little (if any) guidance to translate LCA result into eco-design recommendation. The findings of this evaluation of LCA tools are in line with the findings of Casamayor and Su (2012), who compared detailed LCA software with streamlined LCA screening tools. They concluded that a LCA tools with a higher number of advanced features are „*not very useful for designers/engineers at design stages, where product designers are more concerned with time and 'hot spots'*" (ibid, p613).

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[34] The evaluation criteria were set up and customised for the special needs of LCA users (section 6.5) in on the basis of the software usability guidelines suggested by the Testing Standards Working Party (http://www.testingstandards.co.uk/usability_guidelines.htm).

A key lesson learnt from the evaluation of existing free LCA tools is the importance of an intuitive way to use the tool with no previous training to the user. Hence, the graphical user interface (GUI) should have a 'look and feel' design. The user's interaction with the tool must be as effortless as possible, for instance having a look-and-feel appearance. That means, the tools must be easy to find (via the World Wide Web), effortless to install, and platform independent. Making easy-to-use software tools can lower the hurdles for companies to implement LCA in the product development process. SMEs may seldom need expert-level LCA tools but rather tools for a quick-check of the environmental relevance of design decisions rather than accurate LCA results. To this end, the LCA-to-go project is going to develop sector-specific simplified LCA approaches for SME.

Table 6-2: Evaluation of freely available LCA tools from a non-LCA-expert's perspective. (+ sufficient; o average; - insufficient, n.a. not applicable) Adopted from (Buiter, J.C. 2012).

LCA Tools	Installer & tool execut-	Design of the user in-	Ease of use	Novice user friendliness	Database age	LCA & eco-design	Up to date
Ecocost Database	+	-	-	-	+	-	+
EIOLCA	+	o	+	-	+	-	-
eVerdEE 2.0	+	o	-	-	-	-	-
Ecolizer 2.0	n.a.	+	+	+	o	+	+
LiMaS	+	+	-	-	o	+	+
D4S	+	+	-	-	+	-	+
Nike Design tool	+	+	+	-	-	+	o
Ccalc	+	o	-	-	+	+	+
OpenLCA	-	-	n.a.	n.a.	n.a.	n.a.	n.a.

One common draw-back of all tools evaluated was the unavailability of comprehensive and up-to-date databases with secondary life cycle inventory (LCI) data. The LCI databases included in the tools show major data gaps regarding materials and processes, which are relevant for product design and development. Another major disadvantage of existing LCI databases is the mismatch in the level of detail of extant secondary LCI data and the information needs of SME.

Aspects of improvement on the state-of-the-art of LCA tools:

1. Significant extension of LCI databases with comprehensive information regarding typical engineering materials, subassemblies, production and manufacturing processes. In an optimal case, the user should be able to retrieve compound LCI datasets of typical product components by inserting engineering variables (size, weight, diameter, tex, conductivity, tensile strength etc.).
2. Simplification of the registration and login procedure.

3. Intuitive graphical user interface and user-friendly help function.
4. Elimination of software bugs, dysfunctional software modules, platform incompatibility, and requirement to install uncommon browser plug-ins/extensions. Speed up loading times - slow Internet connection speed or slow database servers should be remedied.

Commendable features of a simplified LCA tool:

5. Abridged sequence of data input forms and visualisation of outputs at one glance.
6. Consequent implementation of the 80/20 rule[35] can help to dissuade the user spending time with the analysis of components that have low impact on the overall result (e.g. small components with low environmental relevance, transport processes etc.).
7. Omission of detailed data quality evaluation in favour of a simple traffic light labelling.
8. Educative links between the LCA-based eco-profile and eco-design recommendation (facilitating the translation of LCA knowledge into the user's common sense).
9. For the user group of fashion/textile designers/artists: The graphical user interface should have an appealing look, preferable using modern ICT platforms (smartphone or tablet computer).

6.4.2. Status and trend in environmental legislation and standards for smart textiles

Presently, environmental regulatory frameworks, EU regulation or national laws do not explicitly address smart textiles. This situation can change in the medium term if smart textiles become successful mass applications. In this case, the legislature may address smart textiles by a range of regulations, just as a variety of novel technologies became subject of regulation in the past. Possibly, the following regulations and voluntary commitment schemes may become relevant for smart textiles in future:

- RoHS Directive 2002/95/EC on the Restriction of Hazardous Substances (EC, 2003a),
- WEEE Directive 2002/96/EC on Waste Electrical and Electronic Equipment (EC, 2003b),
- REACH Registration, Evaluation, Authorisation and Restriction of Chemicals (EC) No 1907/2006,
- Ecodesign Directive 2009/125/EC on Energy related Products (ErP) (EC, 2009),

One possible area of regulation affecting smart textiles is the European WEEE Directive, which addresses waste electronic products. Although it is not yet agreed whether smart textiles are to be considered to be WEEE at the end of their life cycle it appears likely that they will come under the scope of the WEEE-Directive. The smart function is often (but not necessarily) realised by textile integrated electronic components and they will influence the properties of smart textiles during disposal. Presently, the WEEE-Directive does not explicitly address such products in its appendix 1 (EC, 2003b). The closest proxy to this type of embedded electronic devices could be the phrase "other products and equipment" in category 3 (IT and telecommunications equipment) and category 4 (consumer equipment). Also "sports equip-

[35] The practitioner's interpretation of the law of diminishing marginal returns affirms that 80% of the required results can be created with 20% of efforts.

ment with electric or electronic components" from category 7 (toys, leisure and sports equipment) and "other appliances" from category 8 (medical devices) may describe e-textiles. There is much space for interpretation. For instance, German Federal Administrative Court decided that chip-equipped sports shoes are not to be considered as electronic devices (EEE) according to German ElektroG ("BVerwG 7 C 43.07," 2008). However, heating mats were judged in another court trial to fall under the definition of WEEE.

Regulation, such as WEEE and RoHS, as well as eco-labelling schemes, may impose certain consequences on product design of smart textiles. Moreover, producers and importers of these products may fall under the provisions of extended producer responsibility in future. In effect, companies may need to provide documentation (e.g. material content, chemical substances and residues, or recycling rates) or even complete environmental product declarations (EPD) according to the ISO 14025 standard to authorities or their customers. LCA could provide useful assistance in this regard.

Table 6-3: Noteworthy aspects of environmental legislation & norms for smart textiles

Relevant aspect	**Items „Environmental legislation & norms“**
Materials	**RoHS** Directive: ban of certain hazardous substances in electronic products **REACH** Directive: only relevant if new chemicals are used in the production chain of smart textiles (but not for nano materials) **Eco-labels:** restriction of chemical residues and chemicals in textile products and -production; minimal water and energy use
Energy	**ErP** Directive: incentive for energy efficient product design – not directly applicable to smart textiles
End of life	**WEEE** Directive: setting collection, recycling and recovery targets for electrical goods, but electronic components in smart textiles are not directly addressed.

Next to regulatory frameworks, there are standards and voluntary commitment schemes for eco-labelling, which are relevant for the smart textiles sector. The international standard ISO 14025:2006 defines the framework for Type III Environmental labels and declarations (ISO, 2006b). Environmental product declarations (EPD) are a means of business-to-business communication in regard to the environmental performance of products. EPDs become more and more important in the supply chain of textile products. SMEs gain a competitive advantage if they are able to provide their customers with EPDs. The procedure to create an EPD is based on LCA, which must be coherent to predefined product category rules (PCR). Thus far, no PCRs for smart textiles have been created. Thus, any company aiming for creating EPDs of smart textiles must first initiate the creation of a PCR. As a rule, the PCRs are guided by experiences derived from existing LCA studies in the respective product segment.

Table 6-4 provides a comparison of LCA relevant criteria as covered by the existing textile eco-label schemes, including Ecolabel schemes for textiles (e.g. Ecotex 100/1000, EU Ecolabel, The Global Organic Textile Standard (GOTS), Cradle to Cradle Certification).

Table 6-4: Summarized overview with main criteria to be addressed by textile standards

Label	Criteria						
	Emissions to water	Emissions to air	Energy efficiency	Worker safety	Consumer safety	Restricted chemicals in final product	Minimal water use
Oeko-Tex 100	no	no	no	no	yes	yes	no
EU Eco-label	yes	no	no	no	yes	yes	no
GOTS	no	no	no	yes	yes	yes	no
Cradle to Cradle	no	yes	yes	yes	yes	yes	yes

6.5 Survey of LCA needs and demands in smart textiles SME

6.5.1. Methodology

The survey started with a broad mapping of European businesses in the smart textiles sector. This was undertaken to compile a list of relevant SMEs for the survey. The mapping was supported by a review of literature and online sources, including company communications, press coverage, technology blogs, proceedings from conferences and industry fairs. To get in contact with firms, some conferences and industry fairs were visited and expert networks in the smart textiles research community were consulted. Furthermore, outreach materials and databases of European and national innovation programs related to smart textiles were screened to identify SMEs that participate in these programmes. The range of companies taken into account was in accordance with the definition of SMEs provided by the European Commission (EC, 2005).

Enterprise category	Headcount: Annual Work Unit (AWU)	Annual turnover	or	Annual balance sheet total
Medium-sized	< 250	≤ €50 million (in 1996 € 40 million)	or	≤ €43 million (in 1996 € 27 million)
Small	< 50	≤ €10 million (in 1996 € 7 million)	or	≤ €10 million (in 1996 €5 million)
Micro	< 10	≤ €2 million (previously not defined)	or	≤ €2 million (previously not defined)

Figure 6-1: Classification of SMEs. Source of the figure: (EC, 2005)

The following screening criteria for the mapping of relevant SMEs in the smart textile sector.

- Small or medium sized company or SME-like subsidiary of a larger firm;
- Located in a European country (EU + EFTA[36]);
- Having commercialised smart textile products or intermediate materials,
- or demonstrated prototypes, design concepts or services related to smart textiles,
- or are involved in smart textile innovation funding schemes,
- or are part of the smart textile value chain (e.g. system integrator).

In total, 53 firms were identified and shortlisted and contacted. The questionnaire-based survey was conducted between April and July 2011. The SMEs were contacted by email and/or

[36] European Free Trade Association

phone calls. A few participants answered the questionnaire at the occasion of face-to-face meetings or phone interviews. In total, 25 SMEs responded to the questionnaire based survey or answered questions by phone (response rate = 47%). 22 SMEs did not answer at all and 7 SMEs (13%) refused participation, indicating that LCA was not relevant for their business. Table 6-5 shows a classification of the responding SMEs in regard to their main business area. Figure 6-2 shows the geographical origin of SMEs participating in the LCA-to-go survey.

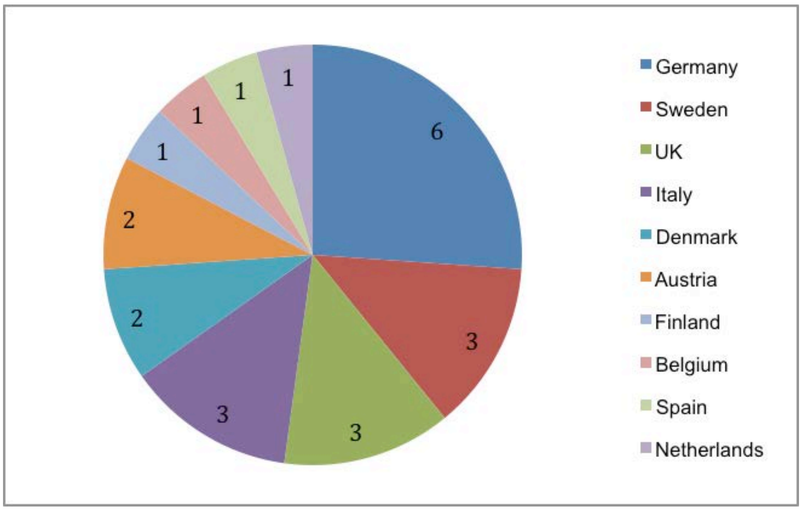

Figure 6-2: Number of smart textile SMEs per country responding to the survey

Table 6-5: Classification of responding SMEs

Larger companies and brands of both sectors (textile and electronics) that consider expanding their product portfolios by smart textiles consumer and business products.	0
Matured SMEs from textile sector that want to innovate by taking up new technologies – providing intermediate materials, B2B solutions etc.	6
Established SMEs from the electronics sector that act as developers for semi-finished e-textile components. Most of these SMEs work as contractors for B2B clients (system integrators).	2
High-tech enterprises: their core business is the development and commercialisation of new technology. Mostly active in B2B niche-markets (such as health care, safety, work-wear).	8
Design service providers and artistic fashion designers, adopting the new technology in a playful manner and experiment with new functions and design concepts. Such SMEs have presented numerous prototypes of smart textiles products at industry fairs and conferences, but few of them seem to have been successful in placing these products in the high street markets.	6
Producers of equipment for textile and electronic industry. Some companies in this branch start to develop industrial machines for smart textiles manufacturing.	0

The survey was targeted at the decision makers or the persons who are responsible for environmental issues in the SME. The questionnaire encompassed twenty-six questions of the following formats: multiple choice, single choice, and open questions. It was developed in the

English and German languages and distributed online. The questionnaire was structured in three parts:

- Part 1 asked for meta-data of the company (name, sector, main products, number of employees, business model). Moreover, the job position of the responding person was noted.
- Part 2 aimed at identifying the experiences of SMEs with environmental assessment methods and LCA in particular. The questions explored the respondent's state of knowledge about environmental aspects of products and the practical experiences with environmental assessments.
- Part 3 requested information regarding the requirements of an environmental assessment tool, i.e. what kind of environmental information the tool should supply.

Subsequent to the questionnaire-based survey, seven phone interviews were conducted among those SMEs that had expressed their interest in the topic. The purpose of the interviews was to validate and complement the findings from the questionnaire-based survey. The interviewees were asked open-ended questions based on an interview guideline, which was customized in terminology depending on the interviewee's area of expertise. All interviewees were asked to respond on questions in three thematic areas:

- Purpose of LCA application (eco-design, environmental monitoring, external communication)
- How should the LCA be represented to provide useful business support?
- How can LCA be implemented in the business processes of a SME (e.g. product development process, EMS, controlling, business strategy support)?

The phone interviews did not aim at empirical robustness; instead they provided more detailed information regarding the actual needs of these companies regarding use and implementation of LCA in their business operations. The analysis was interpretive, paying attention to patterns or trends in LCA application. The survey results (questionnaire and interviews) were then analysed according to the objectives of the LCA-to-go project, focussing on following aspects:

- General insights into the current status quo in SMEs about knowledge and expectations regarding LCA and environmental assessments,
- The decision context situation of a SME,
- Drivers and obstacles for LCA application,
- The SME's needs for LCA and demands on the design of a software tool.

6.5.2. Survey results

6.5.2.1. Status quo of LCA application

Part 2 of the survey explored the implementation of environmental assessments in SMEs. Most SMEs manage environmental tasks (e.g. assuring legal compliance) as a part of regular business activities. The responsibility is with the managing director or the product manager. The survey findings suggest that two-third of the SME, and in particular the small enterprises (less than 10 employees), have no dedicated communication procedure between persons responsible for core business tasks and persons responsible for environmental tasks. This can be explained by the undiversified responsibility of the executive personnel in small enterprises, where leading staff performs multiple duties upon necessity.

Formal environmental management systems (such as ISO 14001) are implemented in only a few SMEs. Only 9% of the responding SMEs have explicitly assigned management duties for environmental management. For comparison, 48% of the SMEs have implemented quality management systems (ISO 9001). A minority of SMEs, whose leaders expressed personal interest and attitudes towards environmental stewardship, seem to execute measures for environmental improvement in an informal manner. A third of the SMEs indicated that eco-design principles are implemented in the product development process. In practice however, none of the respondents indicated to use tools or checklists for eco-design and environmental assessment[37]. SMEs seem to embrace the Cradle-to-Cradle approach as a guiding principle, least for the purpose of external environmental communication. 81% of the respondents were aware that their job position in the company is related to environmental aspects: Product developer (36%) and product manager (8%) can influence the environmental performance of products. 48% of the respondents hold a managing position (CEO, managing director) where they can influence company environmental policies. In general, most respondents expressed a generally positive stance towards sustainable technology innovation but they were lacking incentives to strive proactively for environmental improvements of their products.

The survey results show that none but one of the respondents have ever worked with LCA at their company (Figure 6-3). Only one SME indicated that they have undertaken a full LCA once and have used other tools as well. One larger textile company reported that they commissioned a full LCA study (Lenzing AG, 2010) on textile materials, however not specifically on smart textiles.

The survey failed to identify tangible reasons for the low rate of LCA implementation in SMEs (Figure 6-4). It seems that most SMEs have no experiences because they have no free resources to exert environmental assessment[38]. Moreover, there seems a prevailing believe that these matters are not important for SMEs at an early stage of innovation. Various entrepreneurs interviewed pointed out that their business priority is with the technical sophistication of smart textiles. They expressed the opinion that other actors in the smart textiles innovation system (such as research institutes, authorities) should take care for environmental assessment and eco-innovation of smart textiles. The majority of interviewees indicated to have no exact knowledge on the relevant environmental aspects of their businesses and the environmentally relevant life cycle stages of their products (figure 6-5).

The SME's presumptions on environmental priorities (figure 6-6) have to be interpreted from this background: the respondents seem to base their decisions on common sense rather than

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[37] One survey SME uses KEPI. The same SME is aware of LCA tools but has not used them as yet.

[38] SME from the more traditional textile sector stressed that environmental aspects are becoming more and more important for business success and that their B2B customers demand environmental declarations and/or ask for eco-labels.

on the results of formal assessments. The respondents' estimates seem to be influenced by experiences with legislation (e.g. RoHS directive: hazardous substances; WEEE directive: recycling) and environmental aspects frequently addressed by public media (e.g. energy saving). Textile companies are concerned about fresh water saving and pollution control.

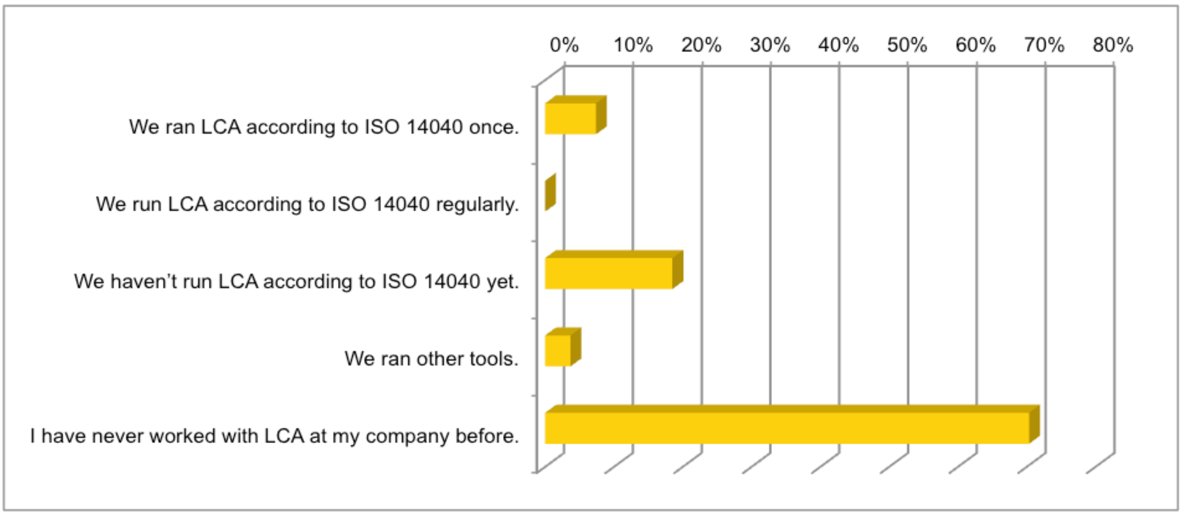

Figure 6-3: State of LCA implementation

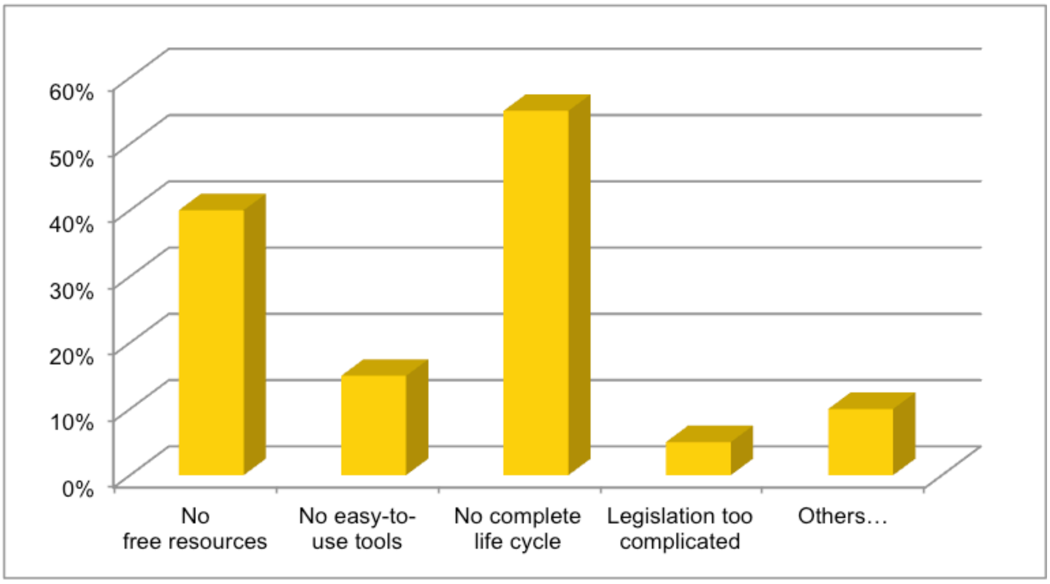

Figure 6-4: Reasons for not running LCA-tools

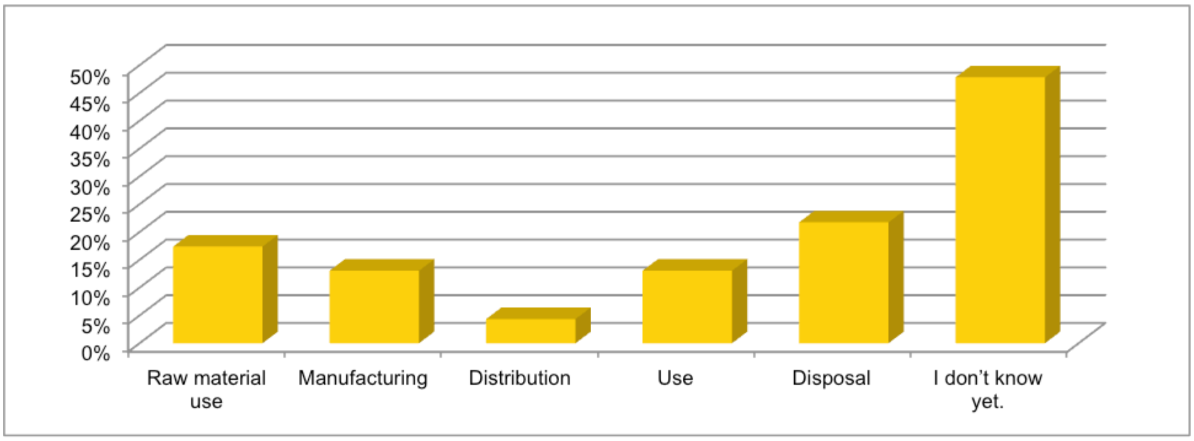

Figure 6-5: Most environmentally problematic life cycle phase according to the interviewees' guesses

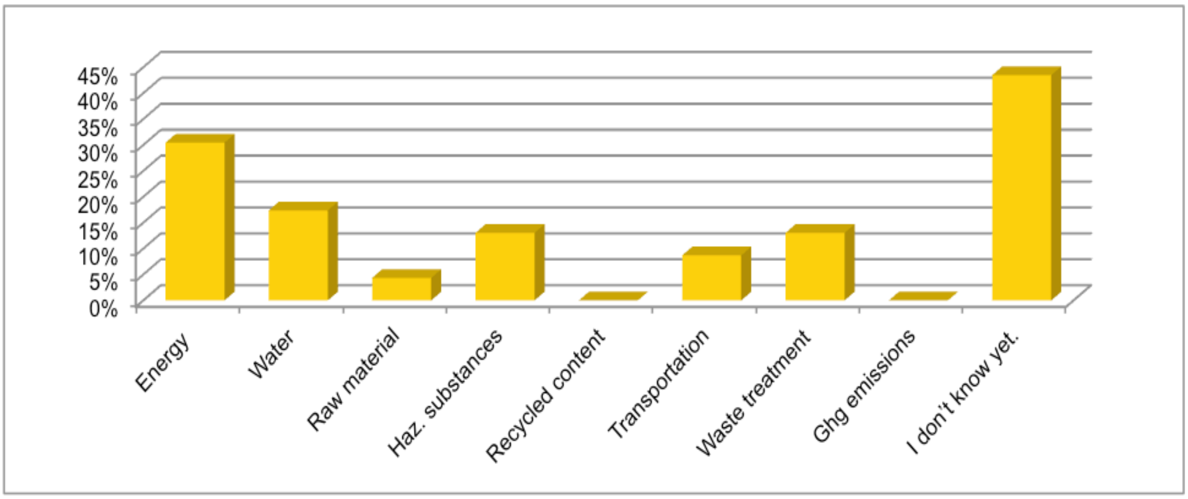

Figure 6-6: Most important environmental aspect according to the interviewees' guesses

6.5.2.2. Needs and demands of SMEs on LCA

Part 3 of the survey exploded the SMEs' wish list regarding an easy applicable LCA tool. In spite of the findings reported above, the smart textiles SMEs seems to have a latent interest in undertaking environmental assessment of their products. At present, only a third of the SMEs indicate that improvements of the environmental performance of products can be seen as a driver for innovations in the smart textiles area. While environmental aspects are presently regarded to have inferior importance as compared to product functionality these aspects are expected to become more relevant in future. 52% of the respondents think the product quality can benefit from improved environmental performance (figure 6-7). The interest in environmental assessment is still not very high among the young SMEs in the smart textile sector. While they are still busy to solve technological problems related to production processes and product functionality they have little incentive to look into environmental life cycle aspects of products.

The situation differs in the more mature textile sector. SMEs in this category are increasingly concerned with improving the social and environmental attributes of their products because their customers (e.g. global fashion brands) are exposed to stakeholder scrutiny and public awareness. Sustainability is regarded an important success factor for future textile business. It may signal the future trend for the smart textile businesses: environmental performance of smart textiles is likely to gain importance as the new sector matures and exposes its products on bigger markets in future.

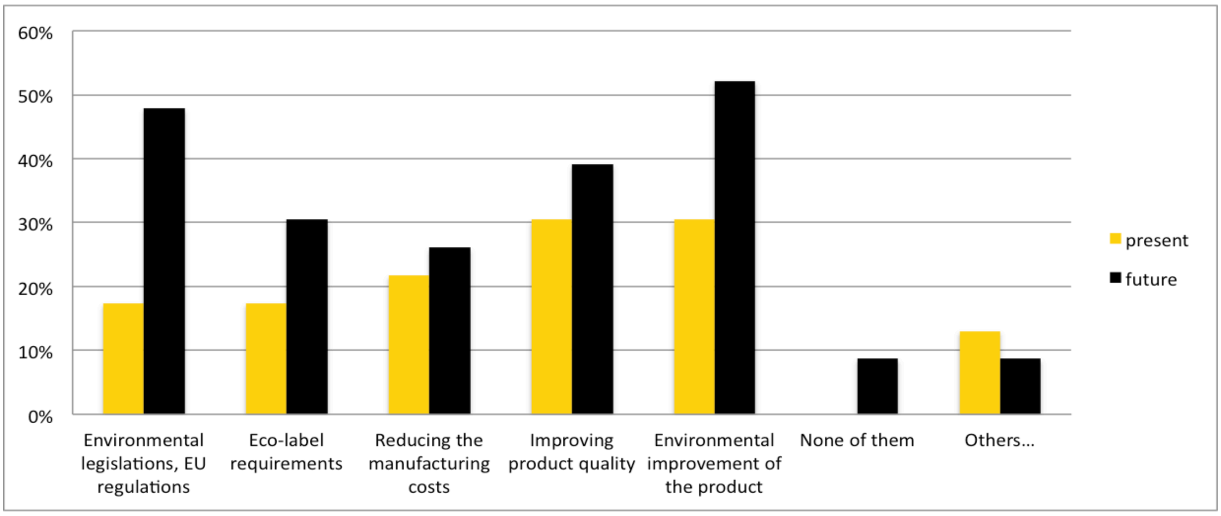

Figure 6-7: Drivers for environmental assessment: present and future product perspective

From the perspective of the businesses, environmental assessment is regarded to become necessary in medium term future due to regulatory requirements. In particular the anticipation of stricter environmental regulation in future seems to fuel concerns of the entrepreneurs. Some interviewees remark that more demanding regulation could hamper the commercial success of the young smart textiles sector. On the other hand, some agree to the idea that legislation can stimulate sustainable innovation, which helps in preserving global competitive advantage of European businesses. They stress, that – most importantly – the legislature must define and communicate clear environmental performance targets early enough in the innovation process.

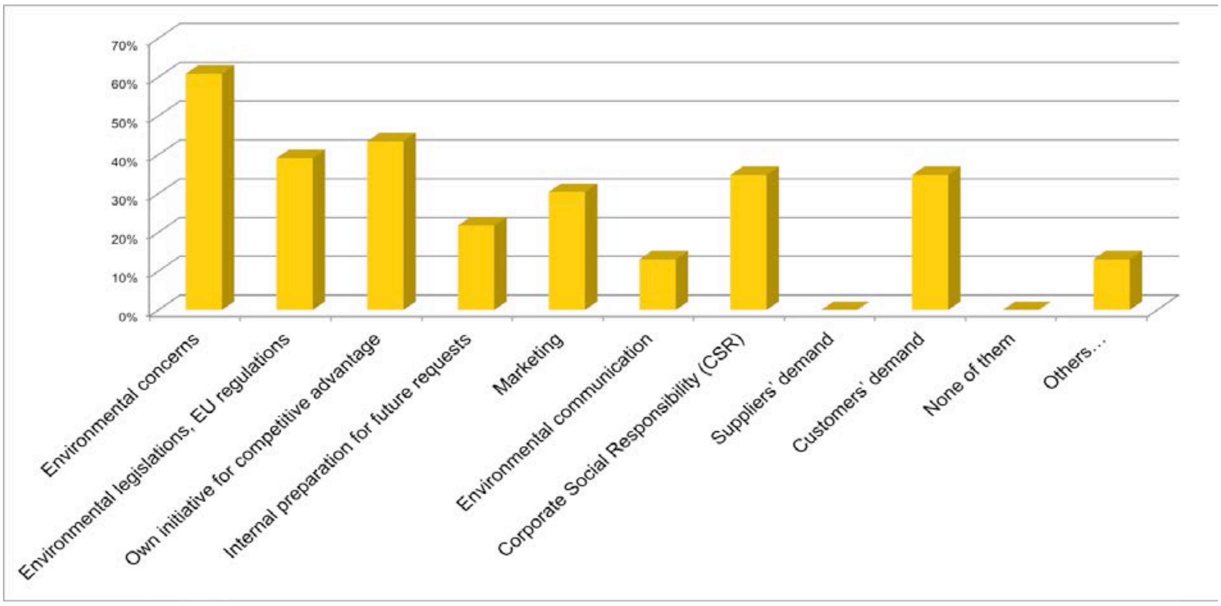

Figure 6-8: Drivers for environmental assessment – company perspective

Figure 6-8 suggests that many of the interviewed persons have a stance of environmental stewardship and social responsibility. This can influence the emerging smart textiles sector. Whereas more than 60% of the respondents seem to be aware of environmental concerns there is no evidence that SMEs implement concrete measures to optimise the environmental performance of future smart textiles products. However, a number of interviewees explicitly emphasised the strategic relevance of sustainable technology development for the future success of smart textiles.

6.5.2.3. Environmental communication

The majority of respondents did not see any advantage of LCA to support external communication (marketing) nor did they see a need to assess and communicate environmental aspects for internal decision support (Figure 6-9). A minority of interviewees however, mostly occupying managerial positions in the respective SMEs, exhibited positive attitudes towards LCA as a support instrument for external communication and environmental improvement (eco-design). As mentioned above, the young smart textiles companies seem to be unaware of environmental aspects being a driver for business development as contrasted to more mature textile companies. They were concerned about compliance of smart textiles with current eco-labelling schemes.

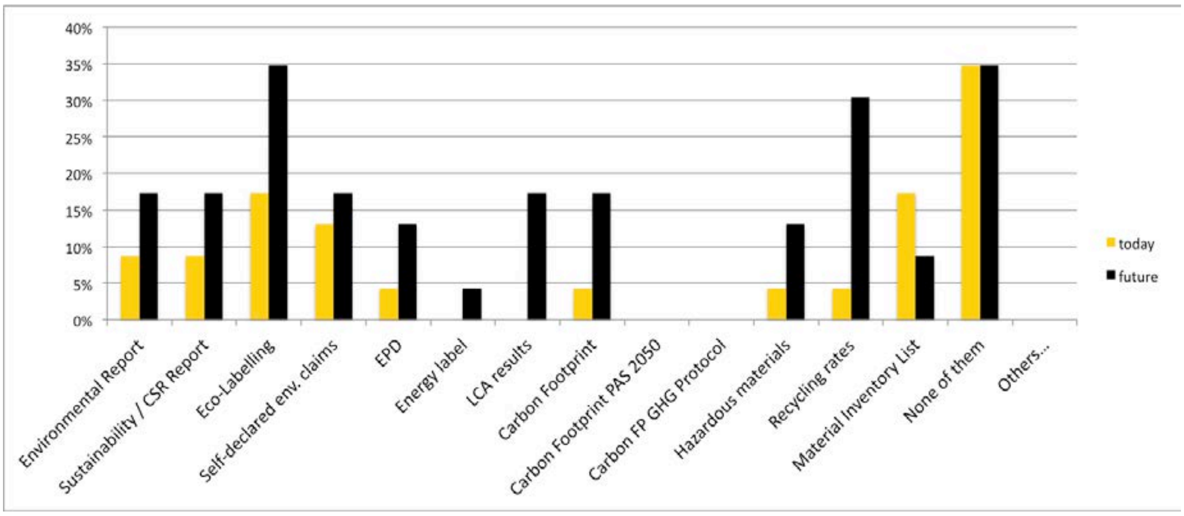

Figure 6-9: Communication tools used today and planned in the future

6.5.2.4. LCA wish list

In general, there were low expectations regarding any LCA tools and most respondents were indifferent in this question. They were obviously lacking experiences in LCA (neither positive nor negative ones) and thus they could not indicate their wishes clearly. Figure 6-10 shows the wide range of criteria that were subsumed under the term LCA. Although not all optional key-words presented in the questionnaire were directly linked to LCA the responses indicate the variety of interests. Energy consumption of products (relevant in the case of electronic textiles) and avoidance of hazardous substances peak out, reflecting some of the environmental key problem areas of high-tech products, alongside with the end-of-life aspects (recycling, resource conservation). During the telephone interviews some SMEs indicated their specific interest in expressing the environmental benefit of their product in the context of the application. Some expect their product to save for example a substantial amount of green house gas emissions compared to the situation without their product and/or with 'conventional' products.

External demand on environmental information is not (yet) a business task for most of the smart textiles SME. Electronic companies are used to material declarations in the context of RoHS compliance and textile producers are sometimes confronted with questions regarding the origin of natural fibre (cotton). There is uncertainty regarding future requirements. In particular in regard to REACH declaration of novel materials such as nano-materials used for advanced textiles.

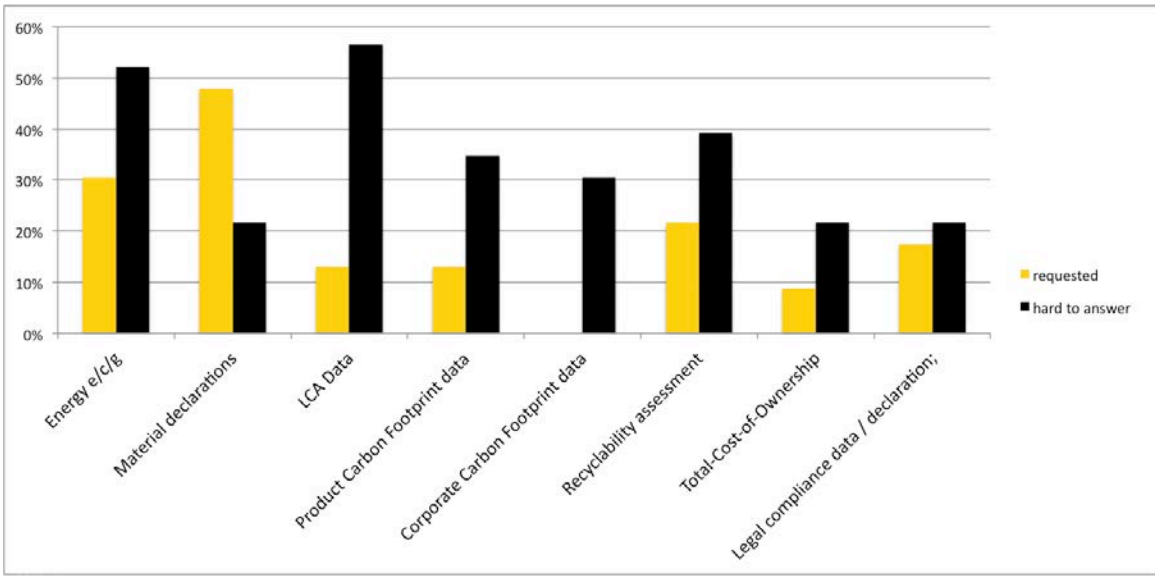

Figure 6-10: Data requested by stakeholders compared with data hard to answer

The expectations on a simplified LCA-to-go tool were rather vague because the responding SMEs were lacking experiences with existing LCA methods. Hence, they were unable to formulate wishes for improvement. A couple of respondents emphasized that any new method or tool must not result in new bureaucratic hurdles to small businesses. For the majority, it appears most useful if results of environmental assessment can provide them with any sort of legal compliance statement or certificate for customer communication.

6.5.2.5. Summary, Wish list of SMEs regarding LCA

In spite of the findings reported above, the smart textiles companies seem to have a latent interest in undertaking environmental assessment of their products. Particularly some of the bigger textile companies have started using environmental assessment results as a marketing tool whereas SMEs seem to have not yet recognised this opportunity. Therefore, the survey among smart textiles SMEs did not yield a clear wish list regarding LCA but it seems possible to draw on experiences from other sectors, such as the classical textile industry and the ICT sector. The following passage gives a short summary of possible LCA needs of smart textiles SMEs in future.

- ✓ It should be possible to assess novel products that contain a large variety of exotic components for which no life cycle data sets exist.
- ✓ The tool will have to be applicable at an early stage of the product development process where uncertainty prevails regarding product specifications, use-scenarios and end-of-life treatment.
- ✓ The tool will be applied in a sector that covers an enormously heterogeneous spectrum of technologies and products.
- ✓ The results of the tool should be represented in an understandable (key-executive) manner, depending on the application purpose (design support or marketing).
- ✓ The EU-Energy Efficiency Label and recycling rates are of most interest for environmental communication.
- ✓ The tool should preferably yield information on legal compliance regarding environmental regulation, EU regulation.

Environmental assessment

- ✓ The tool should support technology developers in early recognition of potential future environmental impacts of smart textiles or certain components thereof.
- ✓ Support design choices with focus on direct environmental impacts: power consumption, hazardous substances, critical raw materials and end-of-life treatment.
- ✓ The tool should include guidelines for the qualitative evaluation of indirect environmental impacts: energy saving potential due to smart functions, replacement potential for technologies with low environmental performance, environmental improvement potential for existing product service systems.

Environmental communication

- ✓ The tool should generate an environmental summary that can be used for bids on call for tenders in public procurement or B2B bids.
- ✓ The tool may support marketing arguments in regard to
    - o energy saving potential (in particular the indirect effects)
    - o compliance to textile eco-labels
    - o recyclability

6.5.2.6. Conclusions from the SME survey

After the survey the specific needs of smart textiles SMEs regarding a simplified LCA tool remained vague. Most obviously, the responding SMEs had little knowledge in and experiences with using environmental assessment methods, such as LCA. The smart textiles SMEs have not yet recognised needs for LCA and have, as yet, not started to deploy LCA as a tool for decision support or marketing. Experiences from the established textile and electronic industries suggest that the incentives to implement LCA will grow as soon as the smart textiles become mainstream applications. At the present, the regulatory framework does not require

SMEs to undertake LCA. However, it appears possible that, in future, the legislature will impose certain environmental specifications on smart textile producers or importers. In future, SMEs may be more interested to use LCA tools if regulatory requirements and customer demands create a demand for eco-designed smart textiles.

The methodological LCA concept for smart textiles needs to be developed with view on future needs (such as possible future regulation). Since the SME, at this early stage of technology innovation in smart textiles, did not clearly outline a wish list for LCA, the potential needs must be anticipated. It can be anticipated that SMEs will become increasingly interested in LCA as the sector matures and products are commercialized in larger market segments. In future, the LCA needs of smart textiles SMEs may be similar to those of the contemporary textile sector.

LCA results should represent environmental indicators that support the decision making of engineers and small business managers (often the same person). Thus, results should be shown at mid-point level in form of engineering units such as energy use, substance-concentration. At end-point level, the LCA results might be aggregated to Eco-costs / Value Ratio (EVR) to allow for benchmarking.

The consequences for the LCA-to-go tool development are twofold: First, it appears useful to adopt an iterative approach of user guidance for the to-be-developed LCA-to-go tool. That may include a pre-selection step for narrowing the application purpose of LCA (e.g. design support, monitoring, benchmarking, reporting) and a detailing step where users can select a calculation output (eco-costs, eco-indicator, PCF, etc.). Secondly, it requires a case-specific approach to the implementation of a decision-support tool in the operation context of a SME in practice. The case-specification should be as generic as possible but detailed enough to represent the different decision support situations (according to ILCD handbook) (EC, 2010).

Taking into account the fondness of designers for appealing visual representation (Lofthouse, 2006), the LCA-to-go software tool should match the habits and customs of the textile/fashion sector. That is, the graphical user interface (GUI) of the tool should be designed in an appealing way and the results should be visualized in such a way that it is easy to interpret for design practitioners (which have little expertise in LCA). Usability of the GUI for non-LCA experts appears to be a key success factor for LCA application in SMEs.

6.6. Life cycle assessment and eco-design of a textile-based large-area sensor system

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Abstract

This section consists of a conference paper, presented at the Electronics Goes Green 2012+ conference. The paper reports about experiences with conducting a LCA in the context of the SME that develops and manufactures the sensing floor system. The process of conducting this LCA case study yielded experiences that supported the development of the LCA-to-go approach for LCA of smart textiles.

The sensing floor is a smart textile application that supports Ambient Assisted Living as it introduces smart functions unobtrusively in the user's daily living environment. The technology is based on textile sensor areas and microelectronic modules, which are integrated invisibly in the textile underlay of carpets or laminates. A Life Cycle Assessment (LCA) was carried out to support environmentally conscious decision-making in the course of product development. The results suggest that the system's electricity consumption during its use phase is the most relevant environmental aspect and that a 2.5 mm thick polyester fleece has the highest environmental burden of the materials in the product.

6.6.1. Introduction

The sensing floor system is an example of an emerging technology that is referred to as pervasive computing. Smart objects enable the idea of Ambient Assisted Living as they provide their users with functions such as personal safety, health protection, and comfort. Textile objects can host smart functions, as they are ubiquitous in the daily living environment. Carpeting, for instance, is a common building interior material. The sensing floor is a smart textile application that is invisibly integrated into the textile underlay of carpets or laminates. This system can be used to support elderly people in their daily life and extends the time they can stay independently and safely at home.

Smart textiles are relevant candidates for environmental assessment. The future environmental impacts of this emerging technology are determined through today's choices in technology development and product design. Smart functions are often realised through electronic devices that are seamlessly integrated into textile materials. The design trend towards product smartness is expected to cause significant environmental impacts once these products proliferate at the mass markets. The total power consumption may increase if myriads of formerly passive objects turn into energy using products (IEA, 2009).

Furthermore, the use of new materials or new combinations thereof can result in environmental problems during the end-of-life treatment of obsolete products (Köhler et al. 2012). Hence, the environmental relevance of design decisions should be evaluated concurrently to the technological innovation process. As long as the production quantities are still small there are good opportunities to implement eco-design principles so as to optimise the environmental performance of the emerging product.

The developers of the sensing floor are interested in identifying the environmental improvement potential of their technology. This is possible by undertaking a Life Cycle Assessment (LCA) of the sensing floor. The LCA method is defined as "*A compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle*" (ISO, 2006). However, conducting LCA ex ante to the product commercialisation is not easy, in particular for small enterprises (SME). The early stage of an innovation process is characterised by a high degree of uncertainty regarding technology specifications, materials and processes, product functions and product use. Information on materials and production processes, being indispensable for the compilation of a life cycle inventory, are often unavailable due to the novelty of the technology. Moreover, life cycle modelling is complicated due to lacking experiences on how future products will be used and disposed of. SMEs are often lacking the resources and the experiences that are necessary to conduct full LCA (Pamminger et al. 2011).

This paper reports key results of a simplified LCA that was implemented at the SME that develops and manufactures the sensing floor system. Results include information on the relevant environmental aspects of the product as well as experiences from the process of undertaking LCA in the context of an innovative SME in the smart textiles sector. The findings support the redesign of the sensing floor to improve its environmental performance. The experiences gained from the implementation of the LCA case study serve as a basis for the LCA-to-go project (LCA-to-go, 2012).

6.6.2. Description of the sensing floor[39]

The sensing floor is a textile-based underlay with integrated microelectronic modules and capacitive proximity sensors (Lauterbach et al 2012). The underlay can be laid beneath practically any type of floor covering and is completely invisible. Unlike a pressure sensor, a textile sensor underlay featuring capacitive proximity sensors can be installed even underneath tiles, stone or wood (Baxter, 1997), has no mechanical parts and features self-test abilities and static signal recognition (Steinhage and Lauterbach, 2008).

A schematic of the sensing floor system is shown in figure 6-11. Basically, a capacitive proximity sensor comprises one or more sensor fields. Inside the sensing floor underlay, the sensor fields are formed by conductive textile-based triangular areas. Eight sensor areas are connected to each microelectronic module in the sensing floor underlay. The sensor events are trans-

[39] This section was authored by Christl Lauterbach, Axel Steinhage, and Axel Techmer of Futureshape

mitted wirelessly (868 MHz) to the transceiver. Its function is to process the sensor events coming from the modules, to analyse the time series and to reconstruct the movement trajectories of the people walking on the floor. When a person walks across the floor, sensor events are detected by the triangular sensor areas beneath the feet.

Whenever a person walks across the floor a sequence of location– and time-specific sensor events is broadcasted. These messages are received by one or more wireless control units. Depending on the application, the receivers can either be embedded devices or PC interfaces. Based on data processing algorithms, such as pattern recognition, these signals can be used to identify various events. Based on this information, the transceiver is able to control wireless switches, which can operate e.g. automatic doors, alarm devices, lights, heating, and traffic counters. It is also possible to send commands to an already existing building control network.

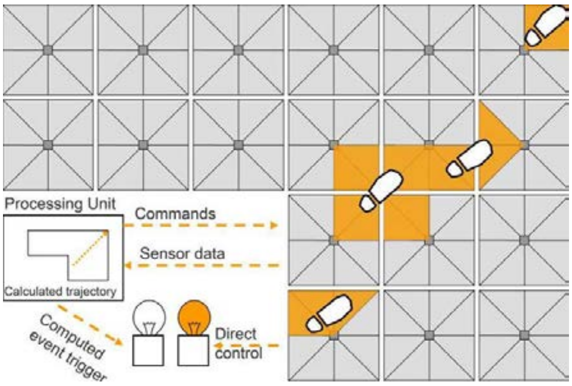

Figure 6-11: Schematic of the system: Footsteps on the floor trigger sensor events. Source: Future-Shape GmbH

The sensing floor can support smart energy management of facilities. A more intelligent control of energy use in buildings is possible when the location and number of people in an area is taken into account. For instance, the illumination of hotel corridors can be dimmed when nobody is around. Air condition can be adapted to the number of people in a room. Unnecessary opening cycles of automatic doors are avoided as the floor can distinguish people walking towards the door or only pass by. A schematic cross section of the sensing floor underlay installed beneath flooring is depicted in figure 6-12.

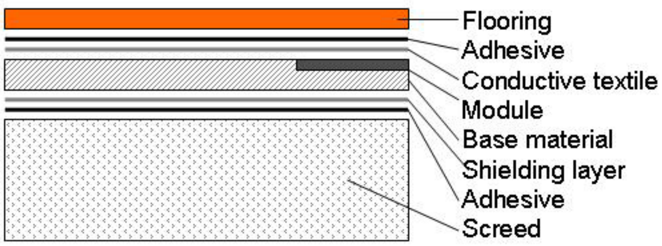

Figure 6-12: Schematic cross section of the Sensing floor underlay installed beneath flooring. Source: Future-Shape GmbH

The active layers are from top: a structured conductive textile layer forming the sensor areas and simultaneously the power supply lines for the integrated microelectronic modules. The modules have a thickness of approximately 1.7 mm. They are connected electrically to the conductive layer and moulded into the base material. The requirements of the base material are: height compensation of the electronic modules, mechanic stabilisation of the underlay during its lifetime and capacitive decoupling of the shielding layer. The shielding layer reduces the noise in the sensor structure and the influence of the material of the base section of the floor.

Every sensor field works like the plate of an ideal capacitor: simply spoken, the capacitance is determined by the proximity (d) of other conductive objects and the area (A) of geometric overlap between the plate and the objects. In addition, the capacitance depends on electrical characteristics of the plate, the object and the material between them. These so-called dielectric characteristics are usually expressed by the constant ε_0= 8.854.10-12 As/Vm and the value εr which describes the dielectric value in relation to that of a vacuum ($\varepsilon_r = 1$).

$$C = (\varepsilon_0 * \varepsilon_r * A) / d$$

The capacitance C2 (figure 6-11) increases with the area of overlap and the dielectric value, and decreases with the distance of the object. Additional contribution to the capacitance is the capacitance C1 of the base material with its shielding layer. Assuming constant material characteristics, the capacitance is directly proportional to the surface area of the objects and inversely proportional to their distance from the floor.

The electrical charge can be stored on the conductive plate when an electrical power source is connected (Texas Instruments, 2007). The charge at a specific point in time t can be determined indirectly by measuring the charging voltage U(t) based on the following equation:

$$U(t) = U_0 * [1-\exp(-t/RC)]$$

Here R is the constant combined resistance of the charging circuit and U_0 is the initial voltage at t=0. As U(t) increases from 0 towards U0 over time following the defined function depicted in figure 6-13, right panel, the capacitance C can be determined by connecting the sensor field to a power source with known idle voltage and to measure the time (t_c) it takes until U(t) has reached a fixed value, e.g. 70% of U0.

The charging time t_c is a measure for the presence and distance of the object as indicated by the three different situations 1, 2 and 3 in figure 6-13. The approaching hand (figure 6-13, left) increases the capacitance C2 and therefore the charging time (figure 6-13, right).

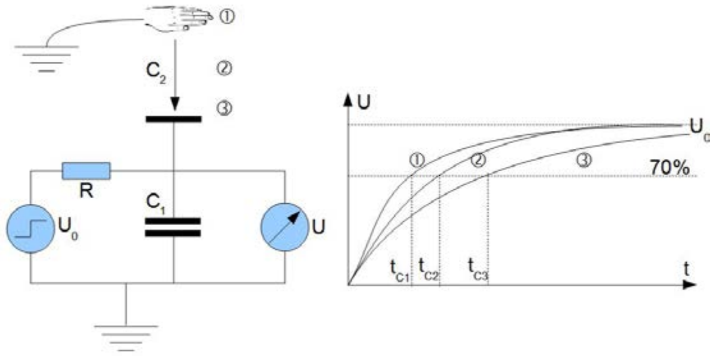

Figure 6-13: Working principle of the sensing floor. The approaching hand (left) increases the capacitance C2 and therefore the charging time is increased (right). C1 is mainly a function of the base material, its thickness and the sensor size. Source: Future-Shape GmbH

6.6.3. LCA of the sensing floor

6.6.3.1. Methodology

The overall objective of the LCA-to-go project is boosting the use of LCA in SME. The project endeavours methodological innovation in life cycle assessment so as to lower the prevailing barriers for LCA-application in businesses (LCA-to-go, 2012). The purpose of the case study on the sensing floor was gaining insights in the opportunities and hurdles of LCA-application by a SME that is at a relatively early stage of product commercialisation. In this specific micro-level decision support situation the intention was to stimulate the SME designing the new products for high environmental performance.

A streamlined LCA was conducted jointly by Future-shape and Delft Technical University within a three-month period in spring 2012. The goal of the LCA was generating information on the prospective environmental impact of the sensing floor. The results are meant to support environmentally conscious decision-making in the ongoing product innovation process.

The scope of this study includes all phases of the product lifecycle (Cradle to grave) as far as information is accessible for the different environmental aspects. The system boundaries of this study encompassed the hardware of the sensing floor. As a simplified assumption the average European energy background system was chosen. The two scenarios were created to test the environmental viability of the sensing floor system during the use phase. For the purpose of the scenario analysis the energy consumption of the application context (room heating and lighting) was included in the system boundary of the LCA.

When compiling the life cycle inventory (LCI) primary data was collected whenever possible from suppliers of half-products. If no primary data was available, data from literature and the eco-costs look-up tables of the Idemat2012 database were used (Vogtländer, 2012). The same inventory provided the data of the impact assessment. The results were calculated as Eco-costs, which is a LCA-based single indicator (Vogtländer, 2001).

For the analysis a fast-track LCA approach, based on the single indicator ‘Eco-costs”, was used. The eco-costs allow for a rapid analysis of the environmental performance of materials, processes and energy use of a product. The approach takes advantage of LCA-based information about eco-costs of materials and processes that are available in form of look-up tables. The indicator describes the sum of all costs to offset the environmental burdens that occur throughout a product’s life cycle "from cradle to cradle". Eco-costs represent virtual prevention costs of emissions as well as materials and energy consumption. The indicator covers the following impact categories: global warming (GWP 100), acidification, eutrophication, summer smog (respiratory diseases), fine dust (PM2), human toxicity (carcinogens), eco-toxicity, and resource depletion, based on midpoint tables of CML-2 and Impact 2002+. Non-LCA experts can comprehend Eco-costs easily by “*by instinct*” as they express a monetary value (€). This is especially practical for SMEs (Vogtländer et al. 2001; Vogtländer et al. 2002).

Interpreting the LCA results lead to the identification of environmental improvement potentials. The recommendations were forwarded to the product developers of the SME as a basis for environmentally conscious redesign of the sensing floor. Preliminary technical approaches to improve the environmental performance were again checked by means of LCA.

6.6.3.2. Scenarios and assumptions

Previous to the LCA, assumptions regarding relevant environmental aspects were made. It was assumed that the textile embedded electronic modules and a shielding aluminium layer might be relevant. It was therefore attempted to acquire more accurate life cycle inventory data from the suppliers of these components. However, this attempt was not successful so that secondary data had to be used. The energy consumption during the use-phase was expected to dominate the life-cycle wide environmental performance of the system. Although measurement data about the power dissipation per electronic module were available there were no experiences on the long-term energy consumption in real application settings. The power consumption of the system, if applied in buildings, depends on its size and operation mode (power-on time). At the same time there are many application areas in which the sensing floor can be used to save energy, for instance preventing undesired opening of automatic doors or switching off lighting in empty rooms. These assumptions influenced the choice of the functional units of the following two application scenarios:

A) Elderly home: Safety and energy management for an elderly person home for 20 years (sensing floor size 30 m^2).
B) Lecture room: Presence monitoring system for a lecture room for 20 years (sensing floor size 4 m^2).

In the first scenario (A), the sensing floor is placed in the house of an elderly person and is used for human fall detection (personal safety). An additional function is to control lighting, depending on room occupation. Also space heating is controlled, achieving estimated 30% energy savings for electricity (lighting) and gas (heating).

The second scenario (B) looks at building automation application. A room occupation monitoring system can save up to 36% of the annual electricity costs for lighting of a lecture room at a university (Becker and Knoll, 2008).

The following assumptions were taken for both scenarios:

- The system is operational 24 hours at 7 days/week for 20 years.
- 6 W operating power for all peripherals (transceiver, adapter and 3 meter of wire).
- No upgrades and maintenance during use phase (no introduction of new parts during use).
- EOL: down cycling of metal coated polyester fibres to be re-used as a additive to anti-static flooring (ESD).
- 3000 km sea freight transport of parts to assembly.

Assumptions on the application context, Scenario A:

- Lighting: 1600 kWh/a electricity (average NL)
- Room heating: 950 m^3/a natural gas (average NL)
- Energy savings potential of 30%
- Assumptions on the application context, Scenario B:
- Lighting: 1440 kWh electricity per year (Becker and Knoll, 2008)
- No heating control
- Energy savings potential of 36%

6.6.3.3. LCA results

Figure 6-14 shows the distribution of eco-costs incurring throughout the product life cycle of the sensing floor (application context excluded). The results confirm the initial assumption that the use phase has the highest environmental relevance. This is due to the continuous power dissipation of the system over a period of time. The difference between the scenarios A and B results from the different size of the sensing floor.

The distribution of eco-costs among the components of the sensing floor are summarised in Table 6-6. The polyester base-layer has the highest environmental impact, mostly due to the weight of the material. Other than expected, the shielding layer of aluminium foil has rather low eco-costs because of its thinness.

The environmental relevance of the textile-embedded modules appears to be moderate. However, the margin of error for these electronic components is high because data unavailability. The relative eco-burden of peripheral electronic devices (Transceiver, etc.) is the higher the smaller the sensing floor application is.

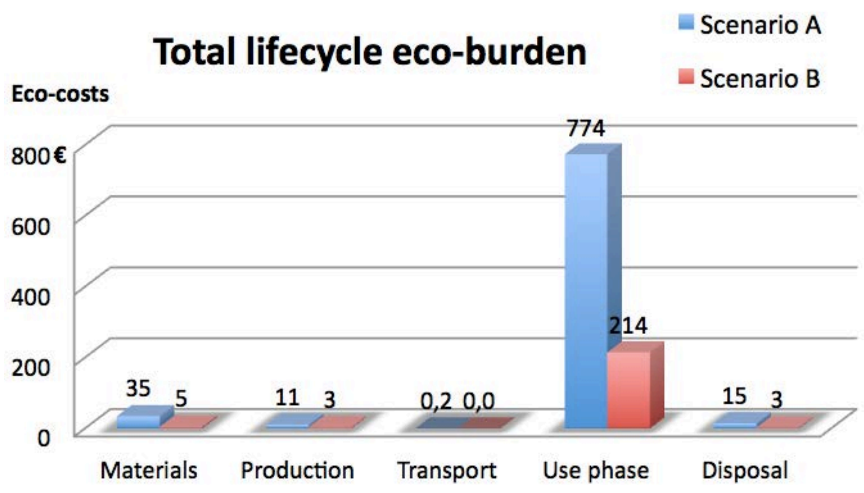

Figure 6-14: The relevance of life cycle stages
(sensing floor size: A=30 m^2; B=4 m^2).

Table 6-6: Relative environmental burden of the components of the sensing floor (in percent of total eco-costs) for the two application scenarios.

Component	**30m^2 size**	**4m^2 size**
Conductive textile (polyester)	6.5 %	4.8 %
Conductive textile (copper/tin coated polyester fleece)	9.2 %	6.8 %
Base material (polyester fleece)	72.8 %	53.4 %
Shielding layer (Al-foil)	1.0 %	0.8 %
Microelectronic modules (4 per m^2)	4.9 %	3.6 %
Adapter	1.6 %	8.7 %
Transceiver	3.2 %	17.8 %
Cables	0.8 %	4.2 %
Total eco-cost	**€ 60,20**	**€ 10,90**

The analysis of the application scenarios (including the energy use of the building) is depicted in figure 6-15. The status quo (bars on the left of both charts) shows the eco-costs of energy consumption in a room without the sensing floor. The middle bars show the application of the sensing floor for building automation. The power consumption of the sensing floor (with current design specifications) offsets the energy saving potential (lighting and space heating). The bars on the right show the energy saving potential of the redesigned sensing floor as described in section 6.6.4.

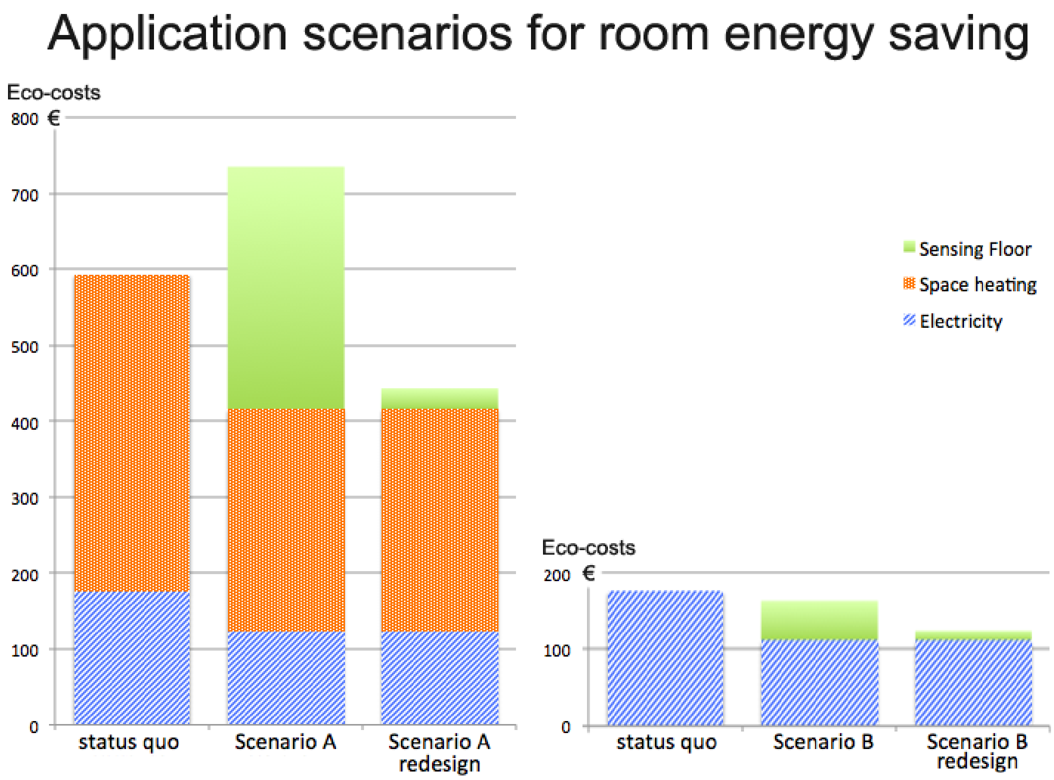

Figure 6-15: Life cycle wide eco-burden of two building automation scenarios. The system boundary encompasses the energy consumption of a room where the sensing floor is installed. (Status quo = room without sensing floor, Scenario redesign = eco-design measures applied to the sensing floor.

The above analysis of the application scenarios is complicated by the high degree of uncertainty regarding the actual energy saving potentials. The assumptions about the elderly home are based on Dutch information on energy use in a single household. No conclusive information has been found whether the elderly use as much energy as a standard single household. Moreover, the actual technical performances of all system components involved vary over a large range as well as the behaviour patterns of different users. When taking all uncertainties into account, the environmental payback time for building automation applications may range from 3 - 45 years.

The products end-of-life treatment is difficult to predict due to its long anticipated lifetime. Waste incineration was assumed as the default scenario. Good recycling opportunities exist for the polyester material as well as the textile-embedded modules. However, these options hardly influence the LCA results.

6.6.3.4. Recommendations for redesign of the product

The LCA results clearly show the high relevance of the power consumption during the use phase of the sensing floor. Currently the transceiver and the floor itself are always on. Thus, investigating possibilities to reduce the power consumption is the most promising approach to increase the product's environmental performance. Moreover, designing out the base material, consisting of polyester fleece, can lower the environmental burden of the product hardware.

Viable redesign options include the use of thinner layers or the substitution of polyester with bio-based or recycled materials.

The LCA results regarding the sensing floor’s capabilities to save energy by building automation are not sufficient as to derive concrete design recommendations. Further investigations of use-scenarios are necessary to reduce the uncertainties in the LCA calculation. As a preliminary direction for product commercialisation, application areas should be searched where the sensing floor helps to lower the demand for space heating of buildings or public spaces.

6.6.4. Consequences for eco-design of the sensing floor

6.6.4.1. Reducing the power consumption

The microelectronic modules within the underlay permanently consume electrical energy to run the measurement process and to listen to radio messages. Each module consumes around 21 mA at 12 V, which sums up to 1008 mW per square meter in the default sensor geometry and at a measurement frequency of 10 Hz for the sensor areas. Several approaches were investigated to reduce this figure.

The reduction of the sensing floor's spatial resolution is an obvious possibility. Only a few applications, such as people counting for instance, require a high resolution of 32 sensor fields per square meter. In most cases a resolution of 2 modules per square meter is sufficient. An underlay with this sensor geometry consumes only 504 mW per square meter. Figure 6-16 shows measurements of four different energy modes and their influence on the power dissipation of the sensing floor during its life cycle for 4 modules per square meter and 2 modules per square meter, respectively. The row 1 in figure 6-16 depicts the power dissipation of the status-quo product.

A second way to save energy is to switch off the radio receiver (Rx) of the microelectronic modules. The receiver is only required when the underlay's configuration or sensitivity needs to be changed by uploading a new parameter set to the modules. This is usually done right after powering up the sensing floor. By automatically deactivating the modules' receivers about 10 minutes after powering up the consumption can be further reduced down to 340 mW and 170 mW per square meter, respectively (Fig. 6-16, row 2).

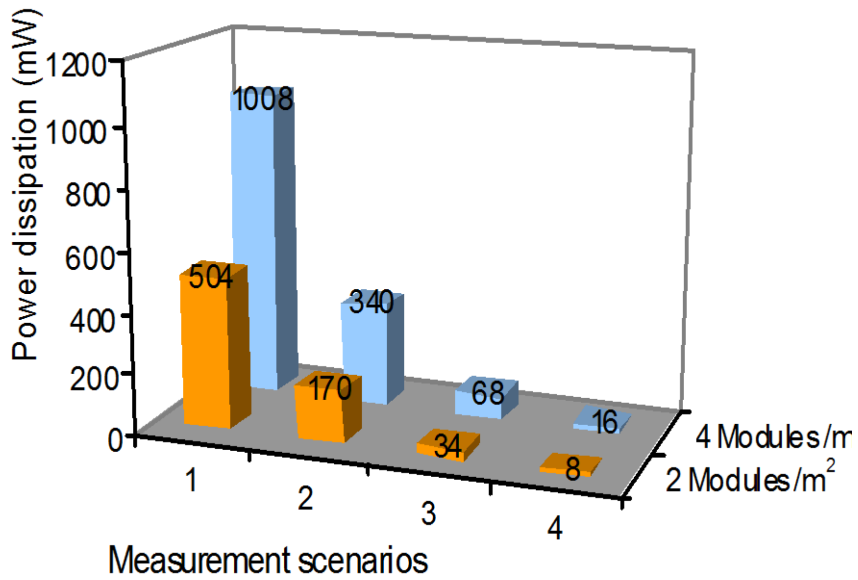

Figure 6-16: Power dissipation measurements for the sensing floor underlay comprising 4 (blue series) or 2 (orange series) modules per m^2. Row 1 shows the power dissipation of the status-quo product. Rows 2, 3, and 4 show different energy saving strategies.

The third possibility is making use of the microcontroller's built-in energy saving functions: at times, when no capacitance measurement and no data transmission is required, the controller can be put to sleep (figure 6-16, row 3). The energy saving effect of this method can be enlarged by reducing the frequency of measurements from 10 Hz (default) down to 2 Hz to prolong the sleeping phases (figure 6-16, row 4). Two capacitance measurements per second are sufficient for most applications.

By implementing all energy saving methods simultaneously the power consumption can be reduced down to 8mW per square meter. Further technical investigations will be undertaken to select an optimal reengineering strategy for the sensing floor. The goal is reducing the power consumption as much as possible while maintaining a product quality that is sufficient for the respective application scenario.

6.6.4.2. Redesign of the hardware

Cork slab was tested as a substitution material for the 2.5 mm thick polyester fleece, being the component with the highest environmental relevance. The component serves as a surface levelling material and capacitive spacer, which requires specific dielectric properties. Various commercially available cork materials were compared. A 3mm thick cork insulation slab was found to be a technically viable alternative. A LCA-based comparison confirmed the environmental advantage of cork slab over polyester fleece (Table 6-7). Cork, being a bio-based material, has lower eco-costs and a lower Product Carbon Footprint (PCF) than polyester.

Table 6-7: Comparing the environmental burdens of polyester fleece and cork slab. Data source: (Vogtländer, 2012).

	Polyester fleece		**Cork slab**	
	Eco-costs €/m^2	PCF kg_{CO2eg}/m^2	Eco-costs €/m^2	PCF kg_{CO2eg}/m^2
Raw material production	0,90	3,3	0,02	0,07
Manufacturing	0,01	1,0	0,18	0,8
Use	0	0	0	0
Waste incineration with electricity	0,13	0,7	-0,14	-0.8
Total	**1,04**	**5**	**0,06**	**0,07**

6.6.5. Lessons learnt from the LCA application in the SME context[40]

The undertaking of the LCA generated experiences about the applied aspects of this venture in a SME context. The LCA was an outward-and-return journey of explorative trials in the framework of a new product development process. The product developers were interested in a rough identification of environmental improvement potentials and the easy comparison of alternative design-solutions or functions. While product developers were knowledgeable about the technical product properties they lacked comprehension of the environmental implications of their design choices. The SME, although motivated to improve the environmental performance of their product, did not have the skills and resources to undertake the LCA without mentoring.

As a consequence, the undertaking of the LCA was not a straightforward series of actions but rather a stop-and-go procedure due to the often-delayed data inquiry from suppliers. The collection of primary LCI data was the most time consuming task of the LCA case study on the sensing floor. Numerous data gaps remain after completion of the three months project period. While data uncertainties are a familiar issue for the experienced LCA practitioner they constitute a major hurdle for SMEs to conduct LCA. The laborious data collection process turned out to be incompatible with the business practice of a fast-moving enterprise.

Concluding from the LCA case study, it is recommended to improve the availability of comprehensive and well-updated secondary LCI data sets. Businesses can benefit from aggregated secondary LCI datasets (on the level of subassemblies) rather than on primary data of basic materials and processes. LCI databases should be amended with comprehensive information regarding typical engineering materials, subassemblies, production, and manufacturing processes. This could be achieved by making LCA a part of publicly founded technology innovation programmes. This way, the European Life Cycle Database (ELCD) could be filled with up-to-date LCI data created on new technologies.

[40] Parts of the paper have been moved to section 6.4.1.3.

6.7. Concept of a LCA-to-go tool for smart textiles

Adopted from: LCA-to-go (Köhler et al. 2012).

6.7.1. Introduction

The smart textiles sector poses particular methodological challenges for LCA. Smart textiles represent an emerging technology, which is still at an early stage of innovation and only a few products have been put to market thus far. The tool approach, outlined in this report, therefore is an attempt to introduce LCA-based information proactively at an early stage of design processes leading to innovative new products. The objective of this section is to address these challenges by developing a sector specific methodological concept for smart textiles.

The smart textiles SMEs expressed fairly ambiguous needs in regard to environmental assessment. Therefore, a feasibility check of the SME's "wish list" on LCA was done in order to maintain the balance of the practical needs and the methodological key elements of LCA. The LCA-to-go tool needed to be developed in anticipation of possible future decision support situations. At the early stage of product development, developers/designers of smart textiles and business executives in SMEs do not need detailed environmental information. Rather, they can take advantage of generic knowledge that leads their design and business decisions into an approximately right direction. To this end, the LCA-to-go concept helps in identifying the key aspect of environmental performance with very little efforts for raw-data acquisition and software training. It is meant to encourage the implementation of eco-design in advance to the commercialisation of smart textiles in future.

1.7.2. Purpose of the tool

The LCA-to-go tool purposes to make LCA-based knowledge accessible to SMEs in the smart textiles sector. The tool is designed as an easy-to-use application for the support of eco-design at the fuzzy front end of new product innovation processes. It builds upon the "to-go" concept: the user's effort to operate the tool and to interpret the results is reduced to a minimum. Therefore, only important environmental aspects are taken into account and the need for sourcing and processing of input data is limited. The tool for smart textiles is intended to be used for company internal decision-making and cannot be used for external environmental communication and marketing.

The tool purposes to:

- Check environmental aspects of typical smart textiles at one glance.
- Provide SMEs with LCA-based eco-design heuristics.
- Provide smart textiles designers with a tool for decision support and reasoning.
- Extend the range of available LCI data with data on smart textiles.

The tool will be primarily adjusted to the needs of design-engineers and leading technology officers at SMEs. The tool can also be used by design agencies and unaffiliated designers/artists who conventionalise smart textiles on behalf of SMEs and larger companies. In addition, the tool offers LCA support to innovators at research laboratories who develop enabling technologies for future smart textile generations. Finally, the tool can be usable for the education of design engineering students at universities and crafting schools.

1.7.2.1. Benefits and usefulness for the companies

The LCA-to-go tool helps SMEs obtaining a first idea of potential environmental aspects of smart textiles. Developers and designers of smart textiles can quick-check the typical ecological profiles of these products to make environmentally benign design choices. This is especially useful in the beginning of the product development process. It helps in avoiding unsustainable design decisions that can make redesign necessary. To that end, the application of the LCA-to-go tool helps in preventing misguided investments in product development and costs of redesign. Moreover, the SMEs can benefit from the LCA-to-go tool as it gives guidance for the creation of environmentally friendly products that have a high added user value. This can lead to competitive advantage in future, in particular under the condition of environmental regulation.

By using the tool, SMEs will gain the following benefits:

- Quick overview of typical environmental aspects of smart textiles without undertaking time-consuming full scale LCA.
- Heuristics for eco-design at an early stage of product innovation.
- Comparison of design options regarding their eco-costs and value ratio.

The tool will not:

- Provide the capacity to conduct a full scale LCA conform to the ISO 14040-44 standard and ILCD handbook (EC, 2010).
- Fulfil the statutory LCA requirements of eco-labelling schemes, environmental product declarations (EPD) (ISO 14025), or environmental compliance schemes (ISO14001, EMAS[41]).
- Create legal compliance statements or environmental claims for marketing purpose.

6.7.3. Framework of the LCA-to-go concept development

6.7.3.1. Objectives

The evaluation of technology specific environmental aspects of smart textiles requires a specific LCA approach that remedies the epistemic uncertainty prevailing at the early stage of the innovation process. The intention is stimulating the development of new generations of smart textiles with improved environmental performance. This is to be achieved through the development of an easy-to-use LCA-based decision support tool for application in innovation oriented SMEs.

[41] Eco-Management and Audit Scheme

Table 6-8: Overall specification of the LCA-to-go approach for the smart textiles sector

Item	Specification
Goal definition	Boosting the application of simplified LCA approach in smart textiles SMEs. The purpose is to stimulate the creation of future products with high environmental performance.
Product system	Smart Textiles (textiles with integrated electronic components)
Functional unit	One product unit providing user value for a period of one year
Time-related coverage	Smart textiles represent an emerging technology that may hit the mass market within one decade. Assumptions on future environmental impacts are based on today's state of knowledge, no predictions are made). The tool allows for creation of scenarios (future situations regarding production, context of use, end-of-life).
Geographical coverage	EU-27 default data as a baseline. Place of production is assumed outside the EU, place of consumption and disposal a present day EU average scenario is assumed.
System boundaries	Streamlined cradle-to-grave
Allocation	Economic allocation
Cut-off criteria	Textile care during use phase (laundry, drying), Small sized textile components and decoration elements. Surrounding network components of a smart system, such as the Internet, data storage in "the cloud" or remote control systems; Data on the average electricity production in the EU (UCTE) replaces for country specific power mix. Second order effects are excluded (e.g. influence of smart textile on the working efficiency of their users).

6.7.3.2. Target user group of the tool

The typical user has an engineering background in textile industry or electronics, that is the user is knowledgeable about technical parameters and functional aspects of the product. He/she can anticipate how the product is used and disposed of. The users' duties in the SMEs are likely to be both, product and process engineer and customer relations.

Typically, the tool is primarily applied within SMEs being at an early stage of product design / redesign process. It may also support technical consultations with B2B customers, possibly be used for sales meetings and at the occasion of industry fairs. The results of the tool are NOT meant to be used for marketing, public comparative assertions, legal compliance statements, or eco-labelling.

Application purpose: product or process-related "Micro-level“ decision support, according to the ILCD handbook (EC, 2010). Quick check of the environmental relevance of design decisions, rough identification of environmental improvement potential, comparison of alternative design-solutions or functions.

6.7.3.3. Target applications

The LCA-to-go tool is intended for the assessment of electronics that is integrated in textile of any kind (wearable and non-wearable). The smart textiles module of the LCA-to-go tool is not designed to cover traditional electronics (i.e. distinct devices carried around in the pocket of a jacket). The smart textile tool is also not specialised for the specific LCA requirements of traditional textile products (e.g. clothing).

Table 6-9: Overview of typical textile products that qualify for smart textiles applications (integration of electronic components)

Wearable smart textiles		**Non-Wearables**
Clothing	**Accessories**	
Jacket, coat, suit, dress (casual & business fashion, sport)	Health & medical devices for ambulant treatment	Health & medical equipment and auxiliary (e.g. hospital bed-clothes, sensor flooring, mats)
Event costume & decora-tions, showbiz	Fashion Accessories: Necklace, bracelet, earrings, wristband, belt	Interior textiles: Home & business furniture, (Sound wall, luminescent curtain, sensor Floor, decorations,)
Underwear (e.g bra) & cas-ual wear (Shirt, sweater)	Shoes, glove, earmuff, scarf	Vehicle interior & upholstery
Sports wear: heart rate monitors (bra, belt), sport shoes,	Home textiles: sensor blanket, heating mat,	Geo-textiles, concrete reinforce-ment textiles
Work wear & protective clothes.	Outdoor & lifestyle accessories: hand-bag, backpack, & other devices	Civil engineering textiles: canvas roofs, awning, canopy
	Wearable computer gaming in-terfaces	Smart labels

6.7.3.4. Decision-context situation

Smart textiles are relevant candidates of an emerging technology that may proliferate at the consumer mass markets in the near future. The widespread application of that new product category is expected to cause significant environmental impacts. The potential future impacts are determined through today’s choices in technology development and product design. The way, how products are designed has a large influence on their environmental performance in the future (Frankl and Rubik, 2000). The current stage of innovation is referred to as the “fuzzy front end” of product innovation (FFI) (Koen et al. 2001). This decision context is characterised by a high degree of uncertainty regarding technology specifications, materials and processes, product functions and product use. On the other hand, the FFE holds manifold opportunities to optimise the technical and functional parameters of the future product for high environmental performance.

Smart textiles SMEs can benefit from LCA-based decision support in day-to-day business operations. The new product development process and procurement are examples of the "Micro-level" decision context situation (A), according to the classification of the ILCD Handbook (EC, 2010). That context is typically characterised by the following circumstances:

- Decisions are related to specific products and do not entail substantial change of the production capacity.
- Limited and no structural consequences outside the decision-context (the SME).
- No large-scale consequences in the background system or other parts of the technosphere.

The micro-level decision support is typically related to product-related questions. Decisions are taken in terms of material/technology selection, choice of suppliers, production methods, and product commercialisation strategies. As such, it is assumed that the consequences of micro level decisions are limited to the direct environmental performance of the product under consideration. The decisions made by smart textile SMEs are unlikely to have direct influence on the large-scale environmental performance of the background system, including other sectors of economy and society. Their direct influence on the background system is low in spite of the innovativeness of the smart textiles technology. Thus, the LCA-to-go tool intended to support specifically decision at the micro-level context. Table 6-10 gives an overview of micro-level decision support situations and their coverage by the LCA-to-go tool for smart textiles.

Table 6-10: Applications of decision support on micro-level and coverage by the LCA-to-go tool

Most relevant applications of decision support on micro-level ("Situation A") (EC, 2010)	**Coverage by the LCA-to-go tool for SMEs of the smart textiles sector**
Identification of Key Environmental Performance Indicators (KEPI) of a product group for Eco-design / simplified LCA	partially (EVR)
Weak point analysis of a specific product	yes
Detailed Eco-design / Design-for-recycling	partially (generic eco-design heuristics)
Perform simplified KEPI-type LCA / Eco-design	yes
Comparison of specific goods or services	partially (scenario analysis of product alternatives)
Benchmarking of specific products against the product group's average	partially (comparison of scenarios of eco-profiles)
Green Public or Private Procurement (GPP)	no
Development of life cycle based Type I Ecolabel criteria	no

Development of Product Category Rules (PCR) or a similar specific guide for a product group	no
Development of a life cycle based Type III environmental declaration (e.g. Environmental Product Declaration (EPD)) for a specific good or service	no
Development of the “Carbon footprint”, “Primary energy consumption” or similar indicator for a specific product	Yes (CED, PCF, EVR)
Greening the supply chain	no, only indirectly via procurement decisions of SMEs
Providing quantitative life cycle data as annex to an Environmental Technology Verification (ETV) for comparative use	no
Clean Development Mechanism (CDM) and Joint Implementation (JI)	no
Development of specific, average or generic unit process or LCI results data sets for use in Situation A	no (but preparatory research being part of this technical report)

The design decisions, taken at the early stage of innovation, have also a strategic dimension in the sense of “Meso/macro-level” decision context situation, according to the classification of the ILCD Handbook (EC, 2010). Design decisions taken at the FFE can determine the choice of technological development trajectories. Technological and design choices at the FFE are likely to have indirect structural consequences outside the decision-context in a more remote future. That can indirectly interfere with the background systems. There is influence potential on the environmental performance of production and consumption processes (second order effects) as well as wider socio-economic impacts (rebound effects). The mass application of smart textiles can influence future raw materials strategies, energy consumption trends and waste policies.

However, such emergent phenomena are hard to predict, in particular from a single innovator’s point of view. The second order effects are intangible from the perspective of SME. Moreover, LCA is inadequate to analyse second order effects because these effects usually reside beyond the system boundary of any assessment framework that is manageable for SME. It would make necessary system expansion and allocations, which complicate the assessment. Hence, the simplified LCA-to-go tool is not designed for Meso/macro-level” decision support.

6.7.3.5. Challenges for a LCA-to-go approach in the Smart Textile sector

Fuzziness in terminology: An unequivocal definition of smart textiles has not been coined as yet. The CEN/TC 248 committee has released a technical report to coin the term “*smart or intelligent textiles*” (CEN 2011). These products are understood as “*functional textiles, which* *interact with their environment by responding to it. This response can be either a (visible) change in the materials properties or result in communicating the environmental trigger to an external read out*" (Byluppala et al. 2011). The absence of an unequivocal and commonly agreed definition of smart textiles makes it difficult to define of the key elements of LCA, including the scope, the functional unit, and the system boundary.

Data challenge: the specific challenge of assessing the life cycle of emerging technologies is the principal absence of relevant data on materials and processes (Rydh and Sun, 2005). Life Cycle Inventory data are unavailable for many of the engineered materials that play a mayor role in the development of new products. The information on the environmental parameters is limited because products do not yet exist and it is hard to infer such data by approximation to other types of products. Moreover, the environmental performance characteristics of prototypes and forerunner products on the market are not necessarily representative for fully matured product generations in terms of efficiency (Eger and Drukker, 2010). Data gaps cannot easily be remedied by analogy to similar inventory data since engineered materials and their production processes are often unique and unprecedented. No LCA studies on smart textile products have been published previously. The lack of up-to-date LCI datasets on high-tech materials is a major obstacle for easy application of LCA in practice. The extant LCI databases show major gaps in availability of materials and processes that are relevant for product design and development. In particular, datasets on emerging technologies, such as smart textiles, are inexistent.

Knowledge gap: Among the innovators who pioneer the development of smart textiles there is a lack of awareness for the possible environmental implications thereof. Businesses recruit engineering and design expertise and these innovators usually have no extra time to spare for getting familiar with LCA methods. Moreover, decision makers in SMEs have often multiple duties, which require knowledge and skills in engineering, business management, and marketing.

A methodological challenge for LCA comes due to the convergence of the formerly distinct life cycles of textile products and electronics. The technology cluster of smart textiles cuts across various industrial sectors (textile industry, electronics industry, medical equipment manufacturers etc.) leading to an increasing complexity in the life cycle models of such combined products. The amalgamation of textile materials and electronics results in more complicated life cycle inventories because new processes and advanced materials are involved. Smartness poses another major methodological challenge for LCA in cases where smart textiles contain networked digital devices. It is hard to define meaningful system boundaries and functional units of products that offer smart functions.

The above-mentioned challenges for LCA of smart textiles are not exceptional for emerging technologies. However, the contemporaneousness of these challenges entails methodological difficulties that go beyond the well-known problems of conducting LCA.

6.7.3.6. Environmental aspects and eco-profiles

For the time being, the accurate evaluation of life-cycle wide environmental aspects is lacking the scientific basis. No LCA studies on smart textiles could be found, and it was also not possible to find any company-published environmental assessment of smart textiles. Extant LCA databases such as EcoInvent, Idemat, ELCD database do not contain specific LCA data on smart textiles. This is due to the data gaps in regard to materials and processes specific to smart textiles. While there are various datasets on base materials that can be used to model a smart textiles specific LCA, any SME browsing these databases will have difficulties compiling a product specific LC inventory. For SMEs it is difficult to know which materials and energy flows are to be selected to model the production of semi-finished materials they purchase from suppliers. Moreover, there are no experiences on the performance of smart textiles during the use phase (washing cycles, battery use, life-span).

More LCA knowledge is available on the environmental aspects of other emerging high-tech products that might serve as an analogy for the situation expected for smart textiles. Moreover, LCA-based knowledge exists for the textile sector. The ABC-analysis below (table 6-11) summarises the existing knowledge on smart technologies that play a role in the context of smart textiles. The ABC-analysis is based on parameters such as potential for improvement, potential influence of SMEs on improvements, relevancy for EU policy, relevancy of a life cycle phase related to the whole life cycle. “A” indicates a high relevancy, “B” a medium, and “C” a low relevancy.

Table 6-11: ABC analysis of environmental impacts and life cycle stages of smart textiles components

	raw materials acquisition		**Processing / manufacturing**		**distribution**		**use**		**end-of-life**	
Synthetic textiles *	**B**	use of fossil oil	**A**	energy consumption	**C**	small relevance	**B**	power consumption, freshwater use, Eutrophication	**B**	not biodegradable
Cotton textiles *	**A**	freshwater use, land use, Eutrophication Human & eco-toxicity	**A**	energy consumption, Ecotoxicity	**C**	Some relevance due to large mass flow	**A**	power consumption, freshwater use, Eutrophication	**C**	Biodegradable
Electronics	**B**	Use of scarce resources, energy consumption, Human & eco-toxicity	**A**	Energy consumption chemical use	**C**	not relevant	**A**	power consumption	**B**	Recycling difficult
Batteries	**B**	Use of scarce resources	**B**	energy consumption, chemical use	**C**	not relevant	**C**	not relevant	**B**	Recycling difficult

SME relevancy	**C**	low influence	**A**	Selection of production technology and location	**B**	Some influence on supply chain shipment distances and transport mode	**B**	Some influence on user behaviour: textile care, use time and frequency,	**A** **C**	Good influence on design for repair, refurbishment, and take-back Low influence on recycling & disposal systems

(* Collins, 2002; Steinberger, 2009; BSR, 2009; Tobler-Rohr, 2011).

On basis of the environmental hotspots identified above and the results of the needs assessment the LCA-to-go tool should focus on the energy consumption for the processing/manufacturing of materials and the power consumption in the use phase.

6.7.4. Methodological concept

The methodological concept of the LCA-to-go tool for smart textiles was created with regard to the specific needs of SMEs in a “micro-level” decision context situation (EC, 2010). In this context, SMEs have a certain freedom of choice regarding environmental aspects of their own operations as well as third-parties, such as suppliers, subcontractors, and their customers.

SMEs have good influence potential on the design of their products and on the environmental performance of the in-house manufacturing processes. Moreover, under the circumstances of a free market, they have choices regarding the raw materials/semi-finished components they procure from suppliers. Although the SMEs have limited influence on the value chain (upstream and downstream) they can usually choose between several alternatives depending on their environmental performance. SMEs are also free to select the target markets for their products and can thus determine the environmental aspects during the product use phase. The LCA-to-go method can support such decisions.

The conception of the LCA-to-go methodology for the smart textiles sector was guided by the “LCA wish list” of SMEs. At first, a feasibility check of the items in the wish list was done. The survey among SMEs unveiled a rather low level of knowledge about environmental issues of smart textiles. Most SMEs have in-house no skills and capacities for LCA and they also lack the knowledge necessary for interpreting the results of existing LCA approaches. Moreover, they have little incentives to exert environmental assessments. The needs assessment yielded only vague insights in the wishes of smart textiles SMEs regarding a simplified LCA tool. The feasibility check of the “LCA wish list” of SMEs resulted in the identification of several collision points with the general methodological concept of LCA. Several wishes, expressed by SMEs during the survey, are incompatible with the life-cycle approach and were disregarded in the method development. For example, the LCA approach is not a suitable instrument for the legal compliance evaluation of SMEs.

In addition, the “LCA wish list” of smart textiles SMEs contains a number of items that are hardly compatible with the objectives of the LCA-to-go project, namely the creation of a simplified LCA tool. Table 6-12 gives an overview of discrepancies of the “LCA wish list” and how they were resolved in the LCA-to-go approach.

Table 6-12: Summary of LCA needs of smart textiles SMEs.

“LCA wish list” of SMEs	Implementation in the LCA-to-go tool
Early recognition of future environmental impacts.	The eco-profiles (step 1) display the order of magnitude of typical environmental impacts. Step 2 allows for a streamlined analysis. Unknown environmental impacts of smart textiles cannot be predicted by means of LCA.
Support design choices with focus on direct environmental impacts	The eco-profiles will be associated with LCA-based eco-design heuristics.
Qualitative evaluation of indirect environmental impacts of smart textiles	The evaluation of indirect impacts is not possible because empirical evidence for such effects is lacking.
Applicable at an early stage of the product development process	The generic eco-profiles (step 1) will be used at the early stage. The number of generic eco-profiles will be limited in the beginning but there is a possibility to update the database as information about new technologies becomes available.
Possibility to assess novel products that contain a large variety of exotic components for which no life cycle data sets exist.	The simplified LCA-to-go approach is not designed to generate LCI data on novel materials. Such data must be created by different means and can then be included in the tool as secondary data (e.g. in Idemat)
Generate an environmental summary that can be used for bids on call for tenders.	The results of the tool can be used for B2B communication (e.g. sales talks). It can aid the designer when reasoning/defending design decisions to clients (or the superior within the company).
Support marketing arguments in regard to energy saving potential, compliance to textile eco-labels, or recyclability. Indicators for external environmental communication: EU-Energy Efficiency Label, recycling rates, legal compliance statement.	The application of the simplified LCA-to-go approach should not be communicated to the public as an LCA endeavour because it is not ISO 14040 conform. Support of eco-labels requirements and legal compliance statements are not necessary because there are none for smart textiles.
The results of the tool should be represented in an understandable manner.	The results are expressed with the EVR, which is used as a highly aggregated output indicator.

Consistency with the International Reference Life Cycle Data System (ILCD) Handbook on LCA.[42]	The "to-go" maxim of simplified LCA may collide with some methodological requirements of ILCD and ISO 14040-44 (e.g. the tool user will not have to document data inconsistencies, perform peer review of his LCA). The generic eco-profiles cannot guarantee technological representativeness for smart textiles in future (due to the prototype character of the existing examples).

At the bottom line, the wish list of SMEs was interpreted as demand for a massively simplified LCA approach and as a call for a user-friendly and intuitively usable LCA tool.

LCA-to-go approach for the smart textiles sector is inspired by the idea that decisions can be aided by information that is approximately right and not totally wrong. Whereas the simplified approach yields less accurate results than a full scale LCA, it can nevertheless be used as a decision support instrument in the context of an emerging technology. This is justified because LCA relevant information about smart textiles is unavailable or at least riddled with a large margin of uncertainty. Moreover, at the early stage of the innovation process designers do not need detailed information on environmental aspects. On the contrary, it matters for them to understand the bigger patterns and to avoid getting lost in an overload of detailed data. For them, LCA-to-go can serve as an early warning system for possible environmental pitfalls in product development so as to get the design strategies right from the beginning.

The proposed LCA-to-go tool for smart textiles consists of two consecutive assessment steps (experienced users can skip the first step)

The step 1 provides the first-time user with a quick overview of typical environmental aspects associated to smart textiles. These generic eco-profiles are based on case studies and previous LCAs so that the tool does not require the user to insert extensive raw-data. The user will be able to tinker with a few variables and get instant feedback on how the adjustments influence the eco-profiles. The change of the eco-profiles are visualised dynamically right next to the data input elements (sliders). Tinkering the variables is a key element of user-interactive learning (as in contrast of a static collection of eco-profiles). The tool will give instant feedback to the user by showing a selection of eco-design heuristics that apply best to the currently selected eco-profile.

The step 2 features a fast track LCA approach, which allows interested users to refine the results of the step 1. By entering step 2, the user demonstrates certain commitment for undertaking LCA, implying that more efforts are necessary to generate more detailed results. The data quality requirements of Step 2 follow the 80/20 rule: it is assumed that 80% of the result can be created by considering only the 20% of input variables that have the highest relevancy. Minor components and less relevant environmental impacts are cut-off.

[42] This point was not explicitly mentioned as a need by SMEs, rather it addresses possible methodological presumptions of LCA experts.

The main feature of a fast track LCA approach is the extensive use of secondary LCI data from databases. Moreover, the selection of LCI data occurs at a level of aggregated datasets for typical engineering materials and semi-finished components/subassemblies rather than on the level of primary raw materials or chemicals. The same goes for processes and emissions. The selection of secondary data sets is preferably supported by technical product properties that are usually made available by suppliers in form of data-sheets. The smart textiles module of the LCA-to-go tool includes date from the Idemat database of eco-costs, which already contains a plethora of data on engineering materials. For the special data needs of smart textiles, the Idemat catalogue needs to be amended with typical smart textiles materials.

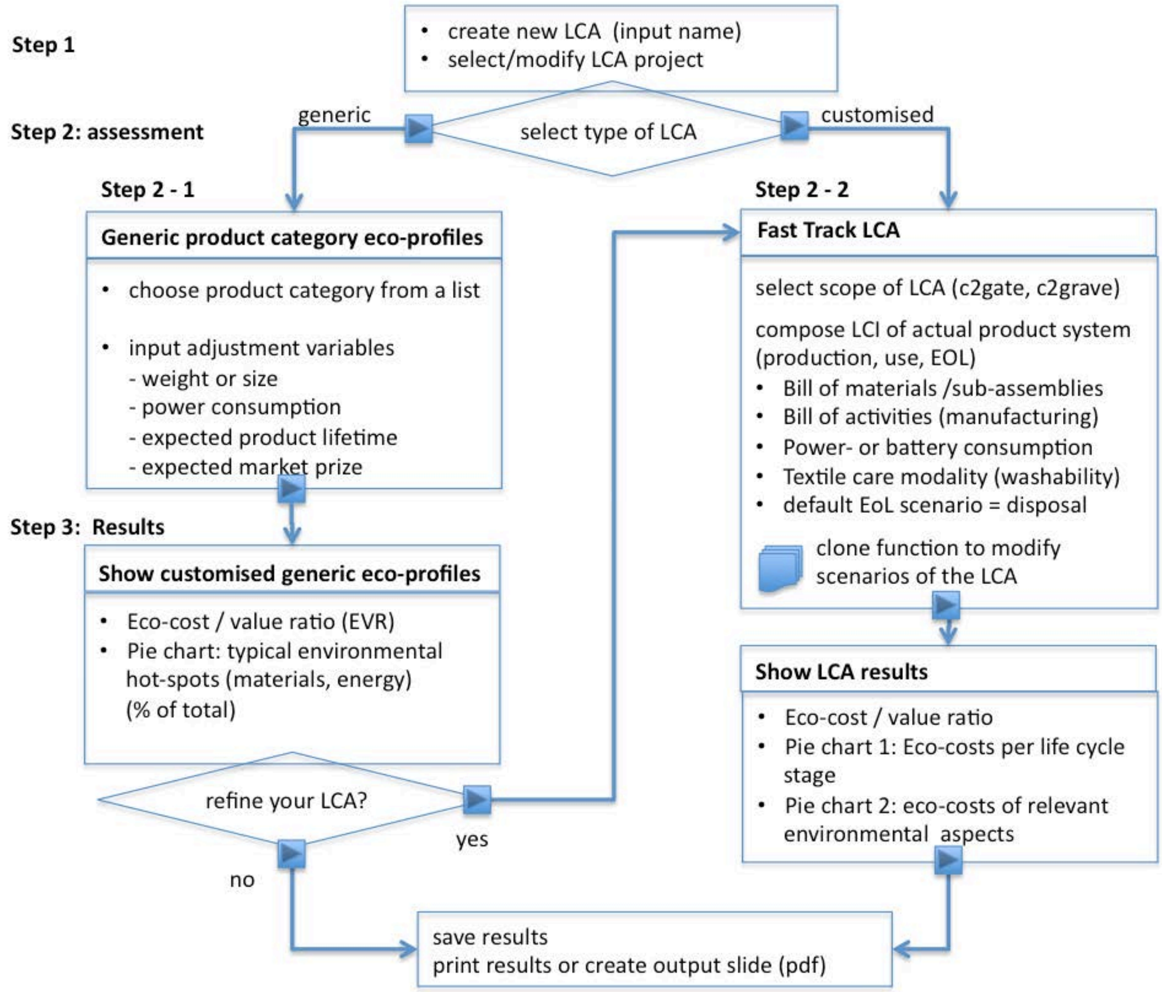

Figure 6-17: The concept of the LCA-to-go tool for smart textiles

6.7.4.2. Data models and algorithms

The micro-level decision support is based on an attributional model, according to the ILCD handbook (EC, 2010). In this context, primary data from the producer should be used whenever available. They can be complemented by data from suppliers and downstream users/customers and secondary data from generic LCI databases. Since the acquisition of secondary data usually is a difficult and time consuming task the LCA-to-go tool integrates the LCI database Idemat.

With view at the representation of LCA results for decision support in the business environment, it was decided to generate single indicator output figures, which are easy to comprehend. The Eco-cost indicator, developed at TU Delft, is a end-point indicator that serves the particular information needs of industrial design engineers in the context of product design processes in practice. The Eco-cost indicator is easily apprehensible for businesses since the result is expressed as a monetary value.

The concept of eco-costs is fully compatible with the provisions of ISO 14040 and ISO 14044. Eco-cost are a single indicator that interprets the results of life cycle impact assessment from a prevention-oriented economic perspective. The indicator describes the sum of all costs to offset the environmental burdens that occur throughout a product's life cycle "from cradle to cradle". Eco-costs represent virtual prevention costs (so to say hidden obligations) of emissions as well as materials and energy consumption the impact categories global warming, acidification, eutrophication, summer smog, fine dust, eco-toxicity, and resource depletion. The eco-costs are comparable with KEPIs in so far they allow for a fast-track analysis of the environmental performance of materials, processes and energy use of a product. The eco-costs avoid the complexity of allocation or system expansion and subjectivity of weighting in LCIA (Vogtländer et al. 2001; 2002; 2009; 2010).

6.7.4.3. System boundaries

The system boundaries of the assessments include

(1) Acquisition of raw materials (covered by secondary LCI datasets, e.g. Idemat)
(2) Production of major components and sub-assemblies
(3) Long-distance transportation for tier 1 components
(4) Use phase (power consumption and batteries)
(5) Disposal (covered by secondary LCI datasets)
(6) Energy supply (covered by secondary LCI datasets)

With these settings, the following processes are explicitly excluded from the assessment:

- Textile care during use phase (laundry, drying),
- Small sized textile components and decoration elements,
- Surrounding network components of a smart system, such as the Internet, data storage in "the cloud" or remote control systems,
- Country specific energy systems (European average UCTE electricity mix as default value),
- Certain technologies sometimes referred to as smart, such as nanotechnology, phase-change materials, shape-memory materials, as well as future technologies that are still at the laboratory stage.
- Second order environmental impacts (improvement potential for other production and consumption processes),

- Future trends in environmental impacts of energy systems, means of transportation,

6.7.4.5. Cut-off criteria

Textile care during use phase (laundry, drying), small sized textile components and decoration elements are aspects that can be neglected in a simplified LCA. Surrounding network components of a smart system, such as the Internet, data storage in "the cloud" or remote control systems; Data on the average electricity production in the EU (UCTE) replaces for country specific power mix. Second order effects are excluded (e.g. influence of smart textile on the working efficiency of their users).

6.7.4.5. Data entries

First screen: shows a list of existing projects (plus one or two project examples). The user can select an existing project out of a drop-down list or create a new project by inserting a new project name in a text input box. It should be possible to clone existing projects (copy previously inserted data to new project name). Further, there should be a function to create scenarios of a project to check the impact of design alternatives (change single parameters). A larger text input box is for a short description of the present user-created project.

Type of assessment: (generic product category eco-profile {goto step 1} / product specific LCA {goto step 2})

Step 1: generic product category eco-profile

The decision of the calculation method remains with the software developers. There are two options: 1) dynamic calculation of the results during runtime of the tool. 2) Creation of ready-made data points, which are stored in look-up tables. If the eco-profiles are generated from a matrix table then they should be stored in a data repository within the tool (not as part of the ELCD or Idemat database).

- Drop-down list of typical Smart Textile applications / product categories (e.g. clothing, medical, work wear, smart label … ca. 10 to 20 items).
- Drop-down list of typical market segments (e.g. consumer products, business/ work applications, technical textiles … ca. 5 to 10 items).
- Checklist of typical product characteristics (variables for the customisation of the eco-profiles):
    - Product weight: [integer] kg
    - Power consumption: [integer] (mW, W)
    - Expected product lifetime: [integer] (days, months, years)

⇒ Calculation method: selection of a predefined generic eco-profile and adjustment according to value of the input variables. The exact number of variables is yet to be defined during the case studies. There should be not more than 3 or 4 variables to keep the first step easy.

In step 1, the data quality requirements are low so as to keep the user's efforts for sourcing of exact information as low as possible. The input variables are based on the user's estimation, and the user is not encouraged to refine the data quality. Therefore, the results of step 1 are not expected to be accurate. Instead, the step 1 results give only a rough orientation of the order of magnitude of eco-costs that are usually to be expected for typical smart textiles.

Step 2: Fast-track LCA of specific products

Input: Materials inventory list (bill of materials) and Weight per item ([integer] kg)

Table of typical components, subassemblies, and semi-finished materials (ca. 30 items in a drop-down list) + text input box for new-created items

Predefined specification of the material composition of each component (aggregated LCI data from Idemat database) will be displayed and can be adjusted by the user (input units: kg; m2, dtex, % to be adjusted via conversion factors). Example:

- Textile material: (e.g. cotton, polyester, acryl)
- [int] g of conductive yarn: (silver coated PE, copper/tin coated PE) [integer] dtex
- [int] cm2 of flexible PWB: (single layer, multilayer,)
- auxiliary materials during use phase (batteries) [int] (number, litre)
- Power consumption (kWh, MJ); a distinction between operation modes should be possible (on / off, stand-by, power save)
    - Use frequency: (disposable, seasonal use, everyday use, long-lasting)
    - Electronic component: [integer] % of product weight

6.7.4.6. Design of the graphical user interface (GUI)

A key lesson learnt from the evaluation of existing free LCA tools is the importance of an intuitive way to use the tool with no previous user training. Hence, the GUI should strictly implement a ‘look and feel’ design (Lofthouse, 2006). The user interaction with the tool must be as effortlessly as possible. The GUI must guide the user through the various steps of LCA and offer guidance and easily accessible help functions for specific LCA aspects. Further, the tool should generate nice and stylish outputs that are not overloaded with technical details or a LCA specific terminology. The eco-costs approach was chosen with having this conceptual requisition in mind.

The tool, in order to be useful in daily business practice should offer the possibility to make side-by-side comparison of scenarios of the same product. Designers are used to compare alternatives, as they are looking at them side by side and tinker with the input variables. Visualisation is crucial. At the FFE, the use of the LCA-to-go tool is not likely to be a consecutive process but rather an explorative undertaking. This is a notable symptom of design processes at the FFE. Thus, there should be a record function that preserves intermediate stages of the eco-profile and LCA exploration. These records are important for the decision making process in groups, such as and brainstorming, presentation, and discussion. To that end, an appealing graphical design should be developed for the presentation of rather abstract LCA information.

While the GUI of the tool should have a look-and-feel appearance (even more important if the user is a fashion designer or artist) the representation of outputs must have a business like appearance. The tool should offer a function to create output slides that are easy to communicate at the occasion of a presentation to the CEO or the client. That is because, at some point, the designer has to present (and defend) the design choices to their superiors or clients. Designers are accountable for the decisions and need to explain what rationales were influencing the design choices (showing the environmental performance of alternative design options). Hence, the EVR is proposed for that purpose as the design choices always affect questions of costs and value creation.

6.7.4.5. Allocation rules for recycling

It is assumed that recycling of smart textiles is not warranted in practice. For the time being, and for the mid-term future the recycling of smart textiles will remain a challenge. It seems unlikely that e-textiles will be included in the regulation of WEEE within the next few years. Hence, the default end-of-life scenario is landfilling. Unless the SMEs have implemented old-product take-back and recycling in their business plans the LCA-to-go tool will not consider a closed-loop scenario. That is to hinder the user of the LCA-to-go tool from resorting to wishful thinking in regard to product recycling (often it is assumed a product is recyclable without further explanation of recycling quotes in reality).

6.7.5. Parameterised Data Models

6.7.5.1. Data Models Step 1

The user starts the assessment by selecting a generic eco-profile of typical smart textiles from a drop down list. Figure 6-18 illustrates the eco-profile of an example product, for which the eco-costs are hosted in a software integrated look-up table. No calculations are necessary at this stage other than the dynamic calculation of the pie-chart figure (percentage of eco-costs). The list of eco-profiles for a variety of products remains to be populated on the basis of LCA case studies. Figure 6-19 shows one example of an eco-profile visualisation.

Kolom1	Impact Total
Material	34,6
Production	14,2
Transport	0,2
Use	397,1
EOL	14,7

Figure 6-18: Example of a generic eco-profile dataset of the SensFloor (impact in eco-cost (€))

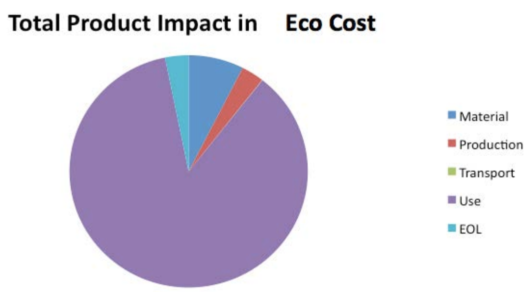

Figure 6-19: Example of the visual output of a generic eco-profile dataset of the SensFloor

Next to the pie chart of eco-costs, a single numerical indicator is displayed as the EVR (eco-cost / value ratio) of each generic eco-profile selected. The use of the EVR has a major advantage over other impact categories (such as PCF, CED): allocation is avoided or multifunctional products because the EVR is based on economic attributes (user value). Hence, the question to what extend the smartness of electronic textiles contributes to the LCA result is easily answered by the user perceived added value of that product property.

The EVR is dynamically calculated during runtime of the tool so as to allow the user to adjust these variables. The EVR is based on the sum of eco-costs divided by the estimated user value in € (Equation 1). Generic data on the user value are contained in the datasets of all eco-profiles (Equation 2).

EVR total = $\{\sum \text{eco-cost}_n\}$ / value total (Equation 1)

where

value total = $\sum$costs + $\sum$taxes +$\sum$profits (Equation 2)

For simplification, the variable ‘value total‘ is based on the user’s estimation of the expected market price of the product from the customer’s perspective (including taxes). In theory, the total perceived user value is higher than the market price. However, it is a difficult to estimate the user-value gained by using the product, in particular for clothing products that are strongly influenced by seasonal fashion trends. The use of market price instead of perceived user value therefore leads to an overestimation of the EVR. That systematic error is acceptable in the context of the FFE, where the overall margin of uncertainty is high.

6.7.5.2. Definition of Data Quality Indicators (DQI) for the Smart Textiles sector

The definition of the DQI scores for the smart textiles sector is presented in Table 6-13. The tailored description will enable the user to quickly identify the appropriate DQI score and provide information on the necessary steps to improve the score should this be needed.

Table 6-13: Data quality table adapted for LCA in the smart textiles sector

Robust	Data is provided by a third party (e.g. supplier) and can be verified. Data is based on measurements over an adequate period of time Data partly based on scientifically grounded calculations or reliable statistics Data applies exactly to the Smart Textile product under investigation. Data applies to a specified area/region Data is less than 6 years old.
Indicative	Data partly based on scientifically grounded assumption or approximation Data are based on secondary LCI data sets. Data gathered over a shorter time period (e.g. a test production batch, user test). Data were derived from previous models of Smart Textiles with similar properties. Data applies to an area/region with similar production conditions. Data is less than 15 years old.
Illustrative	Estimate data not based on measurement or provided information. Data are based on secondary LCI data sets for materials with presumably similar properties. Data gathered over a single testing period or from testing a Smart Textile prototype. Data applies to a different type of Smart Textiles or being compiled from other types of products (e.g. non smart textiles or separate electronic components). Data are inferred from assumptions over future developments or anticipated state of background systems (e.g. supply chains, energy systems, disposal schemes). Data may apply to a different (or unknown) area/region. Data is older than 15 years or the age is unknown. Data gaps cannot be mitigated

The output of the tool should link the results of the LCA to the quality of the input data. This will enable the user to quickly identify which areas of data collection, if any, need to be improved and whether the result is robust. This is of central importance when deriving improvement measures for the product under investigation.

Table 6-14: Generic representation of Data Quality Indicators for Smart textiles

Data quality	Materials	Manufacturing	Distribution	Use	End-of-Life
Robust					
Indicative	x	x			
Illustrative			x	x	x

The overall data quality of all life cycle phases is low, taking the scientific expectations on data quality as a yardstick. In this sense, the LCA results are not very robust because of gaps and uncertainties of input data. In the case of the sensing floor (see section 6.6.) the major draw-back in data quality was due to the uncertainty of the future use-phase, i.e. to what modes the users will operate the product in reality and how the smart functions of the sensing floor can be utilized in combination with existing building infrastructure (such as space heating). Moreover, input data on certain materials (e.g. flexible PWB) and production processes were incomplete or based on assumptions. Secondary LCI data (eco-costs from the Idemat database) were necessary for most components and aspects because no primary data could be acquired. Thus, the robustness of the results is limited.

However, from the perspective of a SME, even non-robust LCA results can provide valuable decision support during the early stage of product development. The results already allow some conclusions to the dominant environmental impacts (here: power consumption) and the life cycle stage in which they occur (here: use phase). Moreover, the results enable the product developer to adjust product properties and to implement eco-design measures before the product is scaled up for mass production.

6.7.6. Further research

Further research remains in terms of creating LCA-based data for generic eco-profiles of typical smart textiles. For this purpose, case studies will be carried out in cooperation with smart textile developers and designers. This includes, trial applications and verification of the methodological concept in practice as well as a refinement of the proposed methodological approach, if necessary to meet the needs of the users of the tool.

After completion of the methodological concept development, the LCA-to-go project has entered the next phase, which includes the programming of a beta version the software tool and the verification of the LCA-to-go approach. This is to be undertaken in form of LCA case studies at a minimum of ten smart textile SMEs. For this purpose, the SMEs are offered free LCA training and coaching in the LCA implementation process. The findings from this implementation phase will, if necessary, be the basis for adjustments of the methodological concept as well as the final release version of the LCA-to-go tool. The implementation phase of the LCA-to-go project exceed the timeframe of the PhD research. Thus, this report does not enclose results of the verification.

6.8. Conclusions

The research was undertaken with the intention to empower designers and developers of smart textiles at SMEs to make environmentally conscious design choices at the early stage of product innovation. For this purpose, the objective of the LCA-to-go project was to lower the barriers for LCA-application in companies that develop smart textiles.

The first research question was dedicated to the characterisation of the current situation: "*What is the status quo of environmentally conscious decision-making in the development process of smart textiles at SMEs?*"

From the results of the literature review and the SME survey can be concluded that environmental aspects are not systematically evaluated and taken into account during the design process of smart textiles. It was shown that LCA is hardly implemented in businesses that develop products that are based on the emerging technology. Existing LCA-tools are difficult to apply at the early design stage due to the lack of information on environmental impacts of materials and production methods. Conducting detailed LCA requires the acquisition of robust input data from suppliers, which is usually a too much time consuming undertaking for SME. Although the evidence suggests that innovators have an interest in environmental improvements of smart textiles, they are lacking adequate support on design decisions. The existing LCA tools are often inadequate for SME. This is mainly due to their methodological complexity (requiring LCA expertise) and due to the time needed to conduct LCA.

The state-of-the-art in LCA-based decision support tools roots in the concept of algebraic algorithms, which help in computing input parameters in order to generate answers on certain questions that emerge in the design process, i.e. 'what is the most relevant environmental aspect of a product?' It is noteworthy that the underlying paradigm of all existing LCA concepts is that of an expert tool. LCA is made for skilled users and provides them with concrete results on specific product related questions. This paradigm entails a twofold problem when LCA is applied in the decision context of technological innovations: 1) It requires a lot of input fairly detailed input-data, which do hardly exist at the early design stage. 2) It presents quantitative results that are difficult to translate in design questions, which are of a merely qualitative nature. In other words, a deterministic assessment method, such as LCA, is inadequate to generate answers on questions that are raised in the beginning of the development of an emerging technology.

This recognition led to the development of a simplified LCA-to-go approach for SMEs in the smart textile sector. Research second question was: "*How can progress be made beyond the status quo regarding LCA application at the early stage of innovations in the smart textiles sector?*

The application of LCA at early stage of technological innovation requires a paradigm shift. If, any progress beyond the state-of-the-art can be made for a sophisticated methodological concept as LCA, then it is animating the user to comprehend the right question in the first place. Instead of generating robust answers to complex questions about the environmental impacts of products the tool should raise the designers' awareness and inspiration. Hence, a simplification of LCA is reasonable for the decision context of an emerging technology if it helps to overcome the barriers that scientifically rigour LCA hinders to be applied in practice. Even if the results of a simplified LCA are less precise than the results of a comprehensive LCA they may provide product developers with preliminary decision support at the early stage of innovation. A simplified LCA may serve as a framework of orientation for eco-design at the fuzzy front of the innovation processes, functioning as an early warning system for possible environmental impacts. An LCA-based tool ought to direct the users' awareness towards the relevant environmental questions and inspire them in their quest for innovative sustainable solutions. In this sense, the proposed approach features simplified eco-profiles of typical smart textiles and combines them with a seed-box of eco-design heuristics. That could be informative to decision makers and lead the product designers to take sustainable trajectories into account right from the beginning.

The proposed LCA-to-go approach for the smart textile sector aims at making LCA-based knowledge accessible to SMEs in order to empower them to address relevant areas of attention at the early stage of the product development process. The tool will support the adoption of eco-design approaches throughout the new product development process, from the fuzzy front until final product design. They will be able to identify the cornerstones of environmental improvement potentials of their products without the need to conduct a full LCA. The simplified LCA-to-go approach for the smart textiles should not be used for product benchmarking, external communication and marketing because the accuracy of the approach is not intended to satisfy these needs. For such purposes, the SMEs will have to use more comprehensive LCA tools (which are available on the market). Moreover, they will have to dedicate more efforts to detailed acquisition of LCI data on their products.

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CHAPTER 7

Material Scarcity – A Reason for Responsibility in Technology Development and Product Design

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7.1. Introduction

Recent disruptions in the industrial supply of certain exotic technology metals have focused new attention on a well-known sustainability issue: resource scarcity. Concern has been voiced over the limits in the future availability of special raw materials, such as rare earth elements (REE), platinum group metals (PGM) and other exotic elements (Angerer 2009; Lifton 2009). Those elements are referred to as 'critical' with regard to their high supply insecurity and their economic and technological importance (EC 2010). Critical elements not only enable the design of high-tech products, but are also key constituents of clean or resource-efficient technologies. The current scarcity with regard to technology metals gives new impetus to the discussion about resource-preserving innovation strategies.

Sustainability experts and economists have repeatedly warned of the consequences of resource depletion throughout the past four decades (Meadows et al. 1972; Simpson 2004; Gordon et al. 2006; inter alia). Although economists have often challenged the notion of resource scarcity (Tilton 2003), the fact that the industrial supply of raw materials is becoming more and more constrained cannot be ignored. There are numerous warning signs that some of the key enabling factors of material abundance (e.g. low energy prices) may not prevail in future. Satisfying the increasing demand will become difficult for geopolitical, environmental and economic reasons (Mudd and Ward 2008).

Nowadays, material scarcity is regarded as an economic and environmental dilemma (Kooroshy et al. 2010). The US Environmental Protection Agency (EPA) points out that "*business-as-usual cannot continue*" because the "*rapid rise in material use has led to serious environmental effects*" (EPA 2009). But it is not only the environmental risks that must be considered; the phenomenon also represents a serious risk to the welfare and prosperity of society because our modern technologies have become fairly dependent on critical elements. Many innovations could come to a halt if critical raw materials become unavailable or are subject to erratic price fluctuations. Emerging businesses, such as the renewable energy sector, will be immediately affected. Low-carbon technologies generate a growing demand for critical elements, but the newcomers on the resource market often lack reliable supply connections. Material scarcity can result in a development barrier for those countries that have few resources of their own and are dependent on raw material imports.

In spite of this, new technology and products have often been developed with little attention to possible constraints in the availability of critical materials. Over many decades, the paradigm of planned obsolescence has governed the design of industrial products (Cooper 2004).

This marketing-driven attitude has resulted in enormous squandering of valuable materials in waste streams. The business-as-usual method has proven to be remarkably successful thus far, which is one of the reasons why many professionals who design and develop new products are under the false impression that the material scarcity phenomenon is a far-fetched problem. Technology developers seem to be relatively unaware of material scarcity and enterprises usually are not well-prepared to tackle the issue (PwCIL 2011). They are still optimistic that technological progress in combination with free market forces will continue to resolve material scarcity just as it has done in the past. However, this kind of resource optimism means that the societal, economic and environmental risks are underrated (Richards 2006). The World Resources Forum (WRF) warns that "*we are losing ever more the freedom to shape the future of humanity*" by continuing the business-as-usual mode of economic growth (WRF 2009).

Limits in the supply of raw materials and energy must be accounted for in the course of technological innovation (Richards 2006; Davidson et al. 2010). Industrial designers and engineers, for example, are directly affected by the symptoms of material scarcity as it limits their freedom of choice in the design process. At the same time, they have a large influence on the consumption of resources. They determine which and how many materials are incorporated into goods. Moreover, their design choices determine how long users will keep a product before replacing it with a new one. Hence, the design engineering discipline has the capacity to lead the change towards the efficient utilisation of resources.

This article discusses the question of whether technology developers should feel responsible for counteracting the risk of material scarcity. The first part of the article reviews the relevance of critical elements for technological innovation and recapitulates the different interpretations of resource scarcity. Then, the concept of sustainable development and the precautionary principle are reconsidered as ethical frameworks for responsibility. The discussion offers arguments for industrial designers and engineers to embrace material scarcity as a challenge to their profession.

7.2. The material base of modern technology

Mineral resources are extracted from the earth's lithosphere to produce and operate technological artefacts. Common base metals, including ferrous metals as well as aluminium, copper, zinc and several alloying metals (e.g. tin, nickel and chromium) play a dominant role in traditional technologies. Meanwhile, the so-called '*technology metals*' have attained a prominent role in industry. Once considered of only marginal technological usefulness, these elements have proven their paramount importance in the progress in science and technology (Angerer et al. 2009; Buchert et al. 2009). Almost every metal or metalloid in the Periodic Table of Elements (PTE) now has technical applications.

The heterogeneous group of materials (Figure 7-1) is referred to in a variety of ways: '*strategic metals*', '*specialty metals*', '*technology metals*', '*green minor metals*' or '*trace metals*'. In contrast to bulk metals, comparatively small quantities of high-tech metals are needed to provide the desired material properties. Nevertheless, the demand for technology metals has grown tremendously. Technological innovation is one reason for the growing demand. Another reason is the mass consumption of short-lived high-tech products, from which the technology metals are difficult to be recycled.

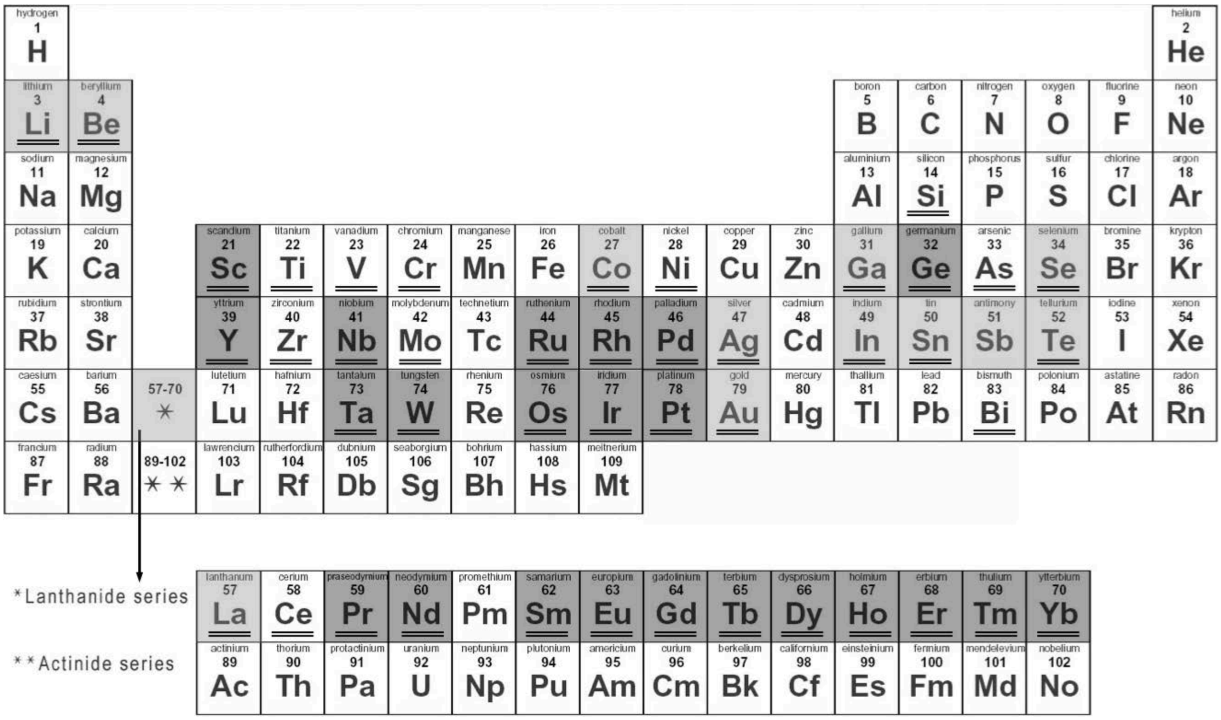

Figure 7-1: Overview of critical elements (grey). A darker shade represents higher criticality. Underlined: technology metals that are used in clean technology and high-performance applications

Technology metals and metalloids are used to produce high-performance components (strong permanent magnets, high-density data storage devices, lasers, etc.). Rare earth elements, for example, are indispensable in the creation of electronic high-tech products and infrastructure. An overview of their technical applications is provided in section 7.7. (Case Study 1). The electronics, aerospace and automotive industries depend on a reliable supply of technology metals, as does the clean technologies sector. Low-carbon energy technologies, such as thin-film solar cells, wind turbines, fuel cells and batteries for electric vehicles, contribute to the growing demand for technology metals. Without these elements, clean technology would perform less efficiently and would have a less competitive cost-benefit ratio.

The impending scarcity of critical materials could slow down the necessary transition towards a low-carbon economy. The European Commission (2010) has warned of a high supply risk for fourteen critical raw materials that play an essential role in the EU economy. Material scarcity, in particular the scarcity of critical metals, constitutes a "*subtle, but further reaching*" risk (Bleischwitz et al. 2008). The US Department of Energy (DOE 2011) has identified a high supply risk for five REE metals that are key materials in clean energy technologies. In addition, shortages in the supply of PGM and various metalloids could "*significantly inhibit the adoption of otherwise game-changing energy technologies*" (APS and MRS 2011). Hence, the issue poses a strategic risk for sustainable development strategies that build on high-tech solutions.

Another aspect that is worth considering is the fate of critical elements when high-tech products reach the end of their useful lives. These artefacts typically consist of bulk materials, which contain small amounts of critical elements. The future trends in smart electronics and ICT foresee myriads of tiny, short-lived devices that will pervade the consumer mass markets (Köhler and Erdmann 2004). As a consequence, critical elements are expected to be dispersed within large waste streams, which will make it very difficult to recycle them (Köhler et al. 2011). It is assumed that a substantial amount of critical elements is lost in waste streams because the recycling rates for electronic waste are very low in most countries (Schluep et al. 2009). With no effective recycling schemes in place, the demand for technology metals is satisfied solely through the extraction of virgin minerals from non-renewable natural deposits, which are continuously depleted as a result. Any further growth in demand will have to be accommodated either by exploration of new mineral deposits or by extracting technology metals from lower-grade resources (Kooroshy et al. 2010).

7.3. Review of different interpretations of the material scarcity problem

Over the last 50 years, more resources have been consumed by humans than ever before (EPA 2009). There are two main reasons for the rapid increase in the demand for raw materials. The first is economic and population growth, and the second the growing consumption of goods and services. Technological innovation has a strong influence on resource consumption in that it facilitates the resource-intensive mass production of high-tech products. Modern technology has led to a substantial increase in resource productivity (e.g. due to the miniaturisation of products) but not to an overall decrease in resource consumption. The bottom line is that the global industrialised economy has caused an unprecedented surge in the consumption of natural resources.

According to Bleischwitz et al. (2008), "*for various commodities, the peak of extraction has already been reached or is currently about to be reached.*" The remaining mineral resources tend to be of a lower grade, which means that their extraction requires more energy and causes higher environmental impacts per unit of raw material (Giurco et al. 2010). The depletion of high-grade mineral deposits coincides with the depletion of accessible mineral oil reserves. The United Nations Environment Programme (UNEP) underpins that '*peak oil*', the point in time at which the maximum rate of global oil is reached, is rapidly approaching or may have already become reality (UNEP 2011). Energy prices are expected to increase in the post-peak oil era. This could exacerbate the material scarcity problem as the extraction of low-grade resources may become prohibitively expensive.

The primary production process of most technology metals is energy intensive and causes large greenhouse gas emissions per mass unit produced (Norgate et al. 2010). Mineral mining is known for its immense social and environmental impacts (Mudd 2010). While the easily accessible mineral deposits are being rapidly depleted, the exploration of remaining deposits is increasingly shifting to remote sites, such as the deep sea and the Arctic. Mineral mining is likely to add to the disruption and pollution of these vulnerable ecosystems (Glaister and Mudd 2010; MMSD 2001; Richards 2006; Mason et al. 2011; Yellishetty 2011). The environmental side effects of increased mining on critical resources can impair important ecological functions (e.g. the marine food chains). A further increase in resource extraction rates will lead to serious reactions by the ecosphere as the impacts of mankind's global economy have already surpassed the environment's safety thresholds (WRF 2009).

The current debate on impending material scarcity reflects a recurring scientific dispute as to whether the exploitation of mineral reserves causes depletion of resources or not. Numerous scholars have repeatedly warned about the scarcity of resources (Meadows et al. 1972; Simpson et al. 2004; inter alia). Communities of environmental experts and economists disagree on how to interpret the phenomenon of material scarcity. The two main positions are summarised below (Tilton 2003; Gordon et al. 2006; Kooroshy et al. 2010).

Fixed stock paradigm: the accelerated depletion of known mineral reserves has repeatedly given rise to concerns over the possible exhaustion of the limited mineral stocks in the earth's crust. The fixed stock paradigm assumes that the total stock of highly concentrated mineral reserves is limited, and that this stock is progressively depleted. The metals are consumed and finally degraded (e.g. due to wear and tear, corrosion and as waste). Moreover, population and economic growth are causing resource depletion to accelerate. If the depletion of non-renewable resources continues, mankind will one day run out of materials in useful concentrations.

Opportunity cost paradigm: the opportunity cost paradigm assumes that the total stock of mineral resources on earth far exceeds human needs. Scientific progress and technological innovations will offset the depletion of high-grade mineral reserves, as new technology will enable access to previously inaccessible/uneconomical reserves. Free market mechanisms balance supply and demand, which keeps the growing demand in check. The only limiting factor is society's willingness to accept the opportunity costs of resource extraction.

Experts have expressed numerous arguments in favour of or in disapproval of these respective doctrines. Proponents of the opportunity cost paradigm refer to historical experiences in which new technologies combined with free market mechanisms have mostly offset the depletion of available mineral reserves. Past long-term trends have shown no dramatic increase in the prices of most mineral commodities (Bretschger et al. 2010).

The historical perspective on raw material availability is often used as an argument for resource optimism (Tilton 2003). On the other hand, some experts warn that we cannot continue in the future as we have done in the past. It seems possible that business-as-usual approaches to dealing with material scarcity may fail in the future (Meadows 2009). The arguments are summarised below.

- Supply shortages for several critical raw materials are likely to occur simultaneously. This limits the possibility of finding substitutes for scarce materials. Furthermore, the erratic occurrence of supply shortages can constrain technological innovation.
- Free market mechanisms may fail due to the high vendor power of countries in which the deposits of critical elements are located. In the long run, material scarcity may result in increasing raw material prices.

- The energy consumption of mining and refining processes increases exponentially as the grade (concentration) of ores declines (APS and MRS 2011). Extracting critical metals from low-grade minerals requires high-grade energy, which is usually taken from fossil fuels. Low-grade mineral resources may be out of reach for future mining due to energy constraints. The peak oil problem amplifies energy constraints (Kooroshy et al. 2010; Tilton 2003).
- From an environmental perspective, the extraction of mineral resources is becoming increasingly expensive (Mudd 2010). These eco-costs comprise environmental pollution, public health impacts, ecosystem and food chain disruption and the displacement of people. Life-supporting functions of nature can be regarded as "*new scarcities*" (Simpson 2004) and must be included in the calculation of the opportunity costs of resource extraction.

One of the fundamental problems in anticipating the future availability of raw materials is the uncertainty regarding emergent phenomena in technological and economic systems. Numerous aspects of modern society, notably population size, climate change and peak oil, are without historical precedent. The significance of forecasts on the possible consequences of resource scarcity is also limited (Peck et al. 2010). Thus, knowledge of the possible consequences of material criticality is limited. The range of uncertainty extends to different aspects, each influencing the risk of raw material scarcity in a different manner:

1) Geological uncertainty: although the total amount of mineral resources on earth is unknown, we know that extraction of known mineral reserves leads to the depletion of these deposits. The peak oil problem also implies uncertainty with regard to future energy costs.

2) Socioeconomic uncertainty: the capability of future technology to access the remaining resources may be under or overestimated. Furthermore, shifts in societal priorities may influence the societal willingness to accept the opportunity costs of resource extraction. This can change as a result of global environmental and social pressures. Political and environmental circumstances can cause market failure (e.g. trade barriers, export restrictions, etc.).

Set against the background of modern technology's increasing dependency on critical elements, and taking into account the uncertainty that exists, the question arises of whether it is fair to proceed with the depletion high-grade resources. This ethical question is closely related to the significance of sustainable development.

7.4. Sustainability as a framework of responsible innovation

Sustainable development (SD) has been defined as a policy goal in the report Our Common Future as a "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (WCED 1987: 43). SD is regarded as a socioeconomic concept that helps to maintain an equitable level of needs satisfaction for the whole of mankind today and for the human generations of the future (Langhelle 1999: 129-149). The Brundtland Commission emphasised the right of development and improvement of living standards for the world's poor. Thus, the concept of SD acknowledges the mankind's right to make use of non-renewable resources as a basis for prosperity. Furthermore, the idea imposes limitations with regard to contemporary needs satisfaction: development today must not impair development in the future.

The essence of this idea is the combination of intragenerational and intergenerational justice. Thus, the ethical principle underlying the concept of SD is the idea of the universal equality of all human beings. Equality in this context is seen as a fair entitlement of all people living throughout the world today (intragenerational justice) to satisfy their essential human needs without this being this to the detriment of people living in the future (intergenerational justice). Strictly interpreted, intergenerational justice is a concept of altruistic human behaviour. It would be revolutionary if implemented at global level. However, even intragenerational justice, which is the fair global distribution of costs and benefits from resource extraction, has not yet been achieved (Richards 2006: 324-333). To that end, the selfish interests of the people living today may be a stronger driver of sustainability, because material scarcity is already likely to limit prosperity within the lifespan of present generations (WRF 2009).

Since the definition of sustainable development was coined in 1987, there has been debate on the extent of natural resource exploitation, which current generations can rightfully commit without compromising the developmental abilities of future generations. This dilemma has led to the emergence of two extreme interpretations of sustainability:

- Strong sustainability: the total natural capital of the earth must be preserved. The depletion of non-renewable resources would therefore be ruled out, and renewable resources could be used only within the scope of their regeneration rate. This interpretation refers to the above-mentioned finite stock paradigm.

- Weak sustainability: the total anthropogenic and natural capital of the earth must be preserved. This means that natural capital can be reduced at will if, in return, human-created capital of the same economic value is substituted for it. This interpretation refers to the opportunity cost paradigm.

It has become apparent that a possible consensus between the two extreme interpretations of SD must be sought as a political goal. The following arguments may be taken into account when searching for a moderate interpretation of SD in the context of material scarcity:

Minerals and metals do not physically vanish when they are used. They are incorporated in the technosphere. This can be seen as a process of substituting human-created capital for natural capital, adding economic value in the sense of 'weak sustainability'. However, usage inevitably leads to a degradation of the quality of materials, due to corrosion, wear and tear, contamination and dispersion in waste. Future generations cannot utilise the same materials in useful concentrations and qualities (Richards 2006). The contemporary depletion of mineral resources must be offset by exploration and acquisition of virgin mineral deposits, which tend to be of a lower grade. It is therefore possible that the energy costs of raw material production will increase to a prohibitive level, thus hindering the ability of future generations to satisfy their needs. This consideration suggests 'strong sustainability', i.e. abstemious use of natural resources in order to preserve them as well as possible.

Future generations have no influence on today's decisions, which will determine the availability of resources in the future. The concept of sustainability imposes a moral obligation on the present generation to act in advance of the future generation's interests. A fundamental difficulty in doing so comes with the fact that we act under conditions of uncertainty and do not know the precise effects of today's decisions. As we do not possess sufficient knowledge about the total amount of resources on earth, how can we then make prudent decisions in technology development? How can we determine the extent of resource consumption that is acceptable in terms of sustainable development?

The precautionary principle (PP) may complement SD as a guide in decision-making under conditions of uncertainty. The PP helps society to make conscious decisions for or against entering into developments that may pose potentially severe or irreversible risks in the long term. According to the maxim of precaution, technology-induced risks should be counteracted before having any adverse impacts on subjects requiring protection (nature and human health). The PP emphasises avoidance of irreversible developments and technological lock-in effects in the innovation process. Preserving a margin of freedom for the decisions and activities of future generations is referred to as the free-space theory of the PP (Beyer 1992). The latter is founded on the two basic ethical principles of justice (intergenerational) and self-determination (autonomy). Thus, the ethical basis of the PP is consistent with SD and leads to the same conclusions: "*...present generations may be obligated by considerations of justice not to pursue policies that create benefits for themselves but impose costs on those who will live in the future*" (Meyer 2011).

7.5.1. Sustainable management of critical materials

Applying the ethical propositions of both concepts – sustainable development (SD) and the precautionary principle (PP) – helps to answer the first question posed in this article: '*Should preventive actions be taken today in order to mitigate resource scarcity in future?*'

The PP leaves no doubt that risks must be counteracted before adverse impacts occur. Material scarcity can have far-reaching consequences because materials are indispensable in the production and maintenance of the technological base of our modern civilisation. On the flip-side, intensifying extraction of the remaining natural resources entails environmental impacts in the form of pollution and damage to the ecosystem. Therefore, resource depletion can arguably be considered a severe risk for people and the environment.

Uncertainty regarding the determinants of the material scarcity problem gives reason to choose the PP as a guiding maxim of judgment: a potentially severe and irreversible risk should be prevented even if there is incomplete knowledge about the risk. According to the "*priority of the bad forecast*" (Jonas 1979), it is better to overestimate a risk (e.g. to assume a small stock of remaining resources) than to underestimate it (e.g. false confidence in future discoveries of new resources). Tilton (2003) stresses that signs of impending scarcity are likely to become visible long before depletion becomes a serious problem. The recent disruptions in the supply of rare earth elements can be interpreted as a warning sign in that sense. A prudent strategy would be to heed early warnings because the depletion of non-renewable resources is irreversible. A precautionary response involves creating awareness of such impending signs before supply shortages become a roadblock for innovation. On the other hand, the stockpiling of raw materials is not a precautionary strategy because, at best, it can only buffer short-term disruptions in supply.

One question remains: why should we reduce resource consumption rates right now? Why not continuing to trust in the ability of future technologies to offset the depletion of mineral reserves? The PP suggests an answer: a margin of safety must be preserved in case future technologies fail to offset exhausted resources. A precautionary strategy means increasing the resilience of modern technologies and business concepts against material scarcity. That requires more than technical solutions alone; it necessitates a paradigm shift in the ways we design, produce, consume and dispose of products.

7.5. The responsibility of technology developers for sustainable material management

The second question posed in this article was: *'Should technology developers feel responsible for taking actions towards sustainable material management?'*

In their self-understanding, the majority of industrial design engineers may agree with the following statement: "Technological progress is good and developing new technology products is therefore 'doing good'." Society as a whole tends to share this point of view as consumers usually cherish the market introduction of new innovative high-tech products. On the other hand, it has become clear that technical innovation often creates new risks. The term "*risk society*", coined by Beck (1986/1992), stands for modern society's solicitude in the face of adverse side effects that can emanate from technology. It also stands for society's expectations that technology developers will 'do no harm', meaning that they will minimise possible adverse side effects.

The moral obligations are beneficence (do good) and non-malfeasance (do no harm). Both obligations are interdependent: someone who is with in good intent is responsible for acting in such a way that no harm is created. Hence, the responsibility borne by industrial designers is twofold. Firstly, in terms of beneficence, they ought to convert natural capital into "*more valuable and durable forms of social capital*" than short-lived high-tech goods, affordable only for an affluent minority (Richards 2006: 326). Secondly, when they create new technology, their mission must include the minimisation of adverse side effects. Acting responsibly in order to prevent future risks can be regarded as one of the provisions of the PP. This concerns an active form of responsibility where the central question is "*what is to be done?*" (Bovens 1998). With regard to material scarcity, the people best able to answer to this question are those who have a causal connection to the potential source of risks: scientists, engineers and designers are the ones who conceive new technology and create demand for critical materials.

Industrial designers, for example, exert a substantial influence on the demand for critical technology metals. Designers give physical shape to ideas and technological visions as they transform abstract technical phenomena (e.g. new materials) into functions that are meaningful to users. Together with other protagonists in the technological innovation system, such as mechanical and electronics engineers, they create new areas of application for scarce materials when they conceptualise new products. Thus, they determine the amount and the fate of the critical elements incorporated in their products. They also determine how consumers use products, e.g. how long products are used before being disposed of (Wahl and Baxter 2008: 72-83). Hence, the designer's influence on the demand and the fate of materials extends well beyond the design phase. The supplementary information to this article, available online, illustrate this in two cases studies: the design of smart textiles and energy-efficient lighting.

Society's perception of the designers' role indeed goes beyond the creation of socially responsible products. They act as "*facilitators of a system of value co-production*" (Morelli 2007: 3-21). By virtue of their profession, industrial design engineers are qualified to 'do good' and have a notable degree of self-determination (autonomy). With the multidisciplinary modality of their work, they are in a good position to contribute actively to the development of sustainable solution strategies (Wahl and Baxter 2008). This implies a collective obligation on the part of designers to prevent the material scarcity risk. They therefore have a form of a virtue-responsibility (Kermisch 2010). Someone who develops new technologies or products bears an active responsibility to consider the consequences of his or her actions (Leerberg et al. 2010). Technology developers should take this role seriously and develop an attitude for sustainable management of critical materials.

7.5.1. What can technology developers do in practice?

A broad discourse among industrial design engineers on resource-preserving innovation strategies is overdue. Although they can by no means solve the material scarcity problem single-handedly, they can work out strategies for sustainable material management. This requires a good understanding of the energy and materials that underlie modern technology. Lifecycle thinking is an important tool that helps technology developers understand the interrelationships between the design of products, consumption patterns and end-of-life treatment of products and the sustainability impacts. This includes a grasp of cause and effect relationships regarding the impacts of design decisions on sustainability. Some of the ideas of what industrial designers and engineers can do to mitigate material scarcity are summarised below:

- Analysing the influence of design decisions on resource consumption and anticipating the fate of critical elements throughout product lifecycles. Engineers possess first-hand information on the material composition of new technologies. By making this knowledge available, they can help to make the scarcity phenomenon more tangible.
- Conceiving viable concepts for the sustainable management of critical materials. For example, exploring ways to design out technology metals from short-lived and low value-added products. This would help to preserve critical resources for applications that are essential for the fulfilment of human needs in the long term.
- Designers can inspire decision makers in politics and industry as they create visions about resource-saving innovation pathways. One possibility is to search for ways to satisfy consumer needs in less material and energy-intensive ways (e.g. dematerialisation).

- Implementing eco-design principles (e.g. design for repair, refurbishment and recycling) in the product development process helps to retain critical elements in a useful embodiment for a longer period of time.
- Taking an active stand for a paradigm shift in industrial design, away from planned obsolescence. By making designs for durable products, they can reduce the wastage of critical elements in difficult-to-recycle high-tech waste.

Design engineering practitioners need knowledge support to respond to the new challenges in an effective and timely manner (Davidson et al. 2010). Multidisciplinary knowledge collaboration with other expert communities can help them to work out sustainable solutions. Particular attention should be paid to the further development of professional skills and qualifications. It is important to train future design engineering professionals to enable them to thrive under circumstances of limited material choices. Thus, sustainable material management should be addressed in education courses for industrial design engineering students (Köhler et al. 2012).

7.6. Conclusions

In following the ethical premises of sustainable development, there is reason to regard material scarcity as a serious risk. The impending scarcity of technology metals can limit the freedom of development and impart innovations in low-carbon technologies in particular. The conclusion reached by the examination of ethical arguments is that material scarcity should be mitigated in the course of the development of new technologies. Uncertainty or ambiguous information regarding the determinants of the phenomenon must not be a reason to ignore a potentially severe and irreversible risk. The precautionary principle offers a framework of orientation for decision-making against the background of this 'wicked problem'. It suggests keeping the increasing demand for critical elements in check so as to prevent the depletion of non-renewable resources. This means, for example, that critical elements should not be squandered in mass-produced applications that have a short service life and that are hard to recycle. To that end, the business model of planned product obsolescence must be renounced.

The discussion elaborated arguments explaining why technology developers should feel responsible for counteracting the increasing demand for critical materials. Technology developers have a profound influence on the demand side (the possibility to act). Moreover, society expects them to consider the consequences of their innovations so as to avoid undesired side effects (collective role obligation). Innovators can and should create viable strategies for resource-aware technology development. They may champion the transition towards more resource-efficient generations of technology. That is, they must not shift the responsibility on someone else, such as the mining industry, the recycling sector or government authorities.

Designers, who have high social reputations, may play a leading role in the sustainable management of critical materials. They can explore technical as well as non-technical options. One possibility is to design out critical elements from products that are not essential for sustainable development. Lifecycle thinking, for example, lends a long-term perspective to the product development process. Eco-design principles can serve as a maxim of action that aims to retain materials in a useful form for a longer period of time.

7.7. Supplementary Information

7.7.1. Case study 1: Critical elements used in electronic products and ICT

This case study takes a closer look at the typical applications of critical elements in electronic products. Contemporary high-tech products have become highly dependent on these elements. Information and communication technologies (ICT) in particular contain a variety of speciality and precious metals (Hagelüken et al. 2010). Mobile phones, for example, contain considerable amounts of valuable materials (Meskers et al. 2009). Their printed circuit boards, on which microchips are mounted, contain metals such as copper, silver and gold. The metals serve as electrical interconnections and heat-dispersing contact structures for corrosion prevention. Small capacitors contain the scarce metal tantalum (USGS 2012). Ferrite cores of high frequency coils can contain ceramic compounds of rare earth element (REE) oxides.

Although many of these scarce elements are used in minute amounts in individual products, they play an indispensable role in ensuring that the electronic hardware performs as required. Transistors, the basic building blocks of contemporary silicon-based microelectronics, consist of crystalline silicon that is doped with tiny amounts of doping elements (Kooroshy et al. 2010). The concentration of dopant elements is usually very low and ranges between 0.1 to 100 ppm in the crystal lattice of silicon. Common dopant elements include aluminium, boron and gallium (acceptor atoms for p-type semiconductors) and antimony, arsenic and phosphorus (donor atoms for n-type semiconductors). Optoelectronic components such as light emitting diodes (LEDs), microwave generators and thin film solar cells use doped gallium arsenide (GaAs) as a substrate material. Doping elements are essential in achieving the desired function for such components. Common dopant elements for GaAs are:

- cadmium, magnesium, silicon and zinc (acceptor atoms for p-type semiconductors)
- selenium, silicon, sulphur and tellurium (donor atoms for n-type semiconductors)

Optical glass fibres are doped with rare earth elements such as dysprosium, erbium, neodymium, praseodymium, thulium and ytterbium (Bass 2010). Table 7-1 provides an overview of the areas of application of rare earth elements (the lanthanide group of the Periodic Table of the Elements [PTE]) in the electronic and electrical sector. Many functional components referred to in Table 7-1 play an essential role in the Internet infrastructure (e.g. server farms and optical and wireless networks) and in low-carbon energy technologies.

Table 7-1: Application areas of rare earth elements in EEE

Scandium (Sc)	Gas discharge lamps, high performance aluminium-scandium alloys
Yttrium (Y)	Phosphors in cathode ray tubes (CRT), oxygen sensors in car exhaust systems, YAG laser rods, component of oxide superconductor materials
Lanthanum (La)	Optical lenses, high refractive index glass for optical fibres, anodic material of nickel-metal hydride batteries.

Cerium (Ce)	TV screens and fluorescent lamps.
Praseodymium (Pr)	Permanent magnets, optoelectronics: optical switch, optical amplifier
Neodymium (Nd)	Permanent magnets used in [electric motors & generators, microphones, loud-speakers, hard disks], ceramic capacitor (dielectric layer), solid-state lasers (Nd-YAG laser rods).
Promethium (Pm)	Beta radiation source, used in nuclear batteries
Samarium (Sm)	SmCo permanent magnets, solid-state lasers, infrared light absorbing optical glass
Europium (Eu)	CRT phosphors, Triphosphors in fluorescent lamps, yellow phosphors for white LED
Gadolinium (Gd)	Permanent magnets, magneto–optical films, microwave technology, green phosphors for CRT and Radar screens, rewritable media CD-RW
Terbium (Tb)	Solid-state devices, e.g. crystal stabilizer of fuel cells, sensors, flat panel speaker, green phosphors in CRT, triphosphors in fluorescent lamps
Dysprosium (Dy)	Permanent magnets, laser materials, hard disks, drive motors for hybrid electric vehicles
Holmium (Ho)	Fluorescent lamps, high-strength magnets, solid-state lasers, microwave equipment, optical glass fibres
Erbium (Er)	Optoelectronics: optical glass fibres, erbium-doped fibre amplifiers, fibre lasers
Thulium (Tm)	YAG laser rods, high temperature superconductors, ceramic magnetic materials
Ytterbium (Yb)	Fibre lasers, optical fibres, solid state lasers

The examples provide only a very rough overview of the pervasive use of rare earth elements in modern high-tech products. The global demand for these elements is rapidly increasing as a result of mass production in the high-tech sector. For example, the rapid growth of the mobile telecommunications sector and the widespread proliferation of mobile phones in consumer markets have resulted in a growing demand for such elements (Soneji 2009). In the near future, the demand for metals that may be used in high-tech products (technology metals) is expected to increase considerably for the following reasons:

- Innovations in the high-tech sector and green technologies are pushing the demand for technology metals. As a result, competition for these critical elements among different emerging technologies is increasing (Angerer 2009).
- Economy-of-scale principles ruling the high-tech sector stimulate mass consumption of electrical and electronic products. At the same time, market size is increasing due to population growth and economic upturn in newly industrialised countries (e.g. India, China and Brazil).

- Consumers tend to use products for ever shorter times. Many products are replaced by newer ones long before the old products cease to function physically, an obsolescence effect that is known as virtual wear and tear.

Table 7-2 presents the material composition of mobile phone handsets found in electronic waste samples. Newer generations of smart phones are thought to contain higher relative amounts of certain critical elements because of their design features. For example, the trend towards large touch screen displays is leading to an increasing demand for indium, which is used in the form of transparent indium-tin oxide (ITO) electrodes.

The example above illustrates the complexity of the material composition of contemporary electronic products. Valuable materials and hazardous substances are often combined in the same product and it is difficult to separate them once they are discarded as e-waste. That, among other reasons, makes recycling of post-consumer e-waste impractical in most countries. Even if the copper and gold in end-of-life products are recycled, the technology metals are mostly lost in the residues (shredding dust of metallurgical slag) (Chancerel et al. 2009). As a result, a high proportion of the valuable materials contained in e-waste is disposed of without recovery.

Table 7-2: Content of valuable metals in discarded cell phones produced around 2003

Material	g per kg	Material	g per kg
Silver (Ag)	1.4157	Iron (Fe)	82.8
Aluminum (Al)	18.9	Mercury (Hg)	0.0000
Arsenic (As)	0.0068	Nickel (Ni)	8.7567
Gold (Au)	0.3261	Lead (Pb)	3.4952
Beryllium (Be)	0.0219	Palladium (Pd)	0.1178
Bismuth (Bi)	0.0489	Platinum & Tantalum (Pt / Ta)	0.0542
Cadmium (Cd)	0.0004	Antimony (Sb)	0.7703
Chromium (Cr)	6.2697	Tin (Sn)	5.3234
Copper (Cu)	116	Zinc (Zn)	3.4275

Source: (Huisman 2004)

7.7.2. Case study 2: Design of smart textiles

This case study takes a closer look at an emerging technology and how developers and designers can influence the content of critical materials in future products. Electronic textiles represent a product design trend that utilises objects of daily life, such as garments, as a platform for smart ICT functions. Textile-integrated electronic devices are currently at an early development stage, and innovation is taking place in the market segments of healthcare, protective clothing for workers and sports clothing. (Schwarz et al. 2010). While garments with integrated electronic devices (e.g. mp3 player or solar cells) have already been put on the market, they have failed to break through commercially thus far (Tröster 2011). However, observers of the innovation system expect e-textiles to proliferate in the mass market within the next decade (Byluppala 2011; Allen 2012).

Although a variety of enabling technologies already exists, they need to be adapted to the new application context of wearable technology (Stylios 2007). Examples of electronic components that can be embedded seamlessly into textiles include sensors, actuators, lighting elements, electronic processing units and elements for power generation and storage (Van Langenhove et al. 2012). Table 7-3 provides an overview of electronic components, which are to be integrated into textile materials.

Table 7-3: Components and materials that are integrated into e-textiles (examples)

Components and application purpose	Examples of materials used
Electrically conductive fibres: - electrostatic dissipation, electro-magnetic shielding, electric wiring and contacting, sensor and actuator elements, power distribution	Copper, silver, gold
	Intrinsically conductive polymers (polypyrrole or polyannilline)
	Conductive polymer composites containing Nano-particles (e.g. silver-NP; carbon nanotubes)
Contacting and bonding elements	Solder alloys: tin, silver, copper, antimony, bismuth
	Conductive adhesives: silver particles
Embedded circuit boards: - mounting and interconnecting of electronic components, mechanical fixation and protection within the textile	Flexible substrata (e.g. silicon elastomers or polyimide film), metals (copper, silver, gold), fire retardants, lacquer
Electronically active devices: - providing ICT functionality (smartness)	ICT devices such as mp3-player, micro-controller and embedded periphery, antenna, RFID-tags, flexible displays and LEDs, etc.
Energy harvesting devices	Solar cells, photoadaptive polymers, piezoelectric materials, thermoelectric generators, (containing e.g. silicon, zinc-oxide, nanoparticles, nanowires)
Power storage	Rechargeable batteries (Li-ion)

The amount of electronic material in e-textiles varies widely depending on the intermediate material used, production methods and application. The metal content of metal-coated fibres can be up to 40 percent by weight. Fabrics with interwoven metallic fibres or silver-ink printed structures (e.g. antennas) can have a metal content of up to 54 percent by weight. Precious metals, such as gold and platinum group metals (PGM), are applied in sophisticated e-textile fibres (Schwarz et al. 2008; Han & Meyyappan 2011). The material composition of textile-integrated electronics is thought to be very similar to off-the-shelf electronic components (table 7-2). These components are incorporated in flexible and stretchable substrates (laminated on fabric or silicone/polyurethane skin). E-textiles tend to require higher quantities of metals as compared to compact devices. Firstly, the textile-integrated electronics are spread over large surface areas. Secondly, in order to make the products fault-tolerant, the electronic structures are usually overdesigned (by using excess material, meander-shaped wiring and redundant structures). Developers strive to make e-textiles that can withstand 25 to 50 washing cycles, which translates into a useful life of less than one year. As such, e-textiles are expected to have rather short service lives and the issue of e-textile recycling has not yet been resolved (Köhler 2011). Critical materials that will be highly dispersed within future e-textiles are unlikely to be recovered from waste. Thus, e-textiles exemplify the prospect of the mass application of high-tech products leading to an increasing wastage of critical elements.

To avoid the depletion of critical materials, developers of e-textiles could adopt existing eco-design principles from the respective sectors of industry (electronics and textile). Textile technology allows for new eco-design approaches for electronics. For example, electronic housing could be made of textile materials instead of metals or plastics. Textile hook-and-loop fasteners allow for easier repair and recycling of old products than screws or clip fasteners. However, many of the existing eco-design principles do not match with the properties of textile-embedded electronics. The design trend towards seamless integration of textile and electronics undermines the 'Design for Recycling' (DfR) paradigm, which suggests designing products for easy dismantling. For example, the widespread use of metal-coated fibres clearly conflicts with the DfR principle of limiting the use of surface-coated plastic. There is a need for new eco-design solutions that suit the emerging technology.

Developers of e-textiles may explore the potentials of new technologies and design critical materials out of e-textiles altogether. Polymer-based electronics, for example, hold promise for the creation of smart functions with lower environmental impacts as compared to silicon-based electronics (Griese et al. 2001; Frazer 2003). Innovations in the field of organic electronics have made rapid progress in recent years (Bettinger & Bao 2010). Although plastic electronics do not match the performance of silicon-based electronics, they offer versatile advantages for the creation of e-textiles. π-Conjugated polymers, such as PDOT, PAni and PPy, can substitute for metals in the form of conductive film electrodes for flexible sensors, antennas and large-area lighting elements. The polymers can be modified as semiconductive materials, which allow for the creation of organic and large-area electronics or fibre-shaped electronics (Mattana & Cosseddu 2011). Semiconductive polymers may have the potential to replace scarce metals in mass manufactured products, including OLED lighting elements, flexible displays and solar cells, film-shaped batteries, roll-to-roll printed logic chips, etc. (Carpi & De Rossi 2005). However, it remains to be demonstrated whether conjugated polymers can fully substitute for critical elements. Prototypes of the technology presented up to now often contain critical elements in the form of transparent ITO electrodes (containing indium) or rear-side electrodes (usually made of silver), light-emitting phosphors (based on REE) or photoluminescent complexes (containing PGM) (Salinas et al. 2011). To that end, the expected mass production of organic electronics could entail increasing consumption of critical elements. Technology developers should therefore bear in mind that rebound effects can occur as they pursue the development of cheap, disposable plastic electronic devices.

7.7.3. Case study 3: Application of rare earth elements in energy-efficient lighting

The proliferation of energy-efficient lighting is a key component of European eco-innovation strategies. The EU is aiming for a 20% reduction in carbon dioxide emissions by 2020. CO_2

emissions can be reduced by 15 million tonnes per year through the adoption of energy-saving lighting in the domestic sector (EU 2008). In order to contribute to the achievement of this goal, the EuP Directive enforces the phasing out of inefficient light bulbs (classes F and G) in favour of more energy-efficient lighting technologies (European Commission 2005). As a consequence, incandescent light bulbs with tungsten filaments, non-directional halogen lamps and 'fat' linear fluorescent tube lamps (T12/T10) have been banned with effect from 2012. The energy-efficient lamps that currently dominate the domestic lighting market are compact fluorescent lamps (CFL) and fluorescent tubes (FT). These lamps are based on gas discharge technology and require fluorescent phosphors to convert ultraviolet radiation into white light. Traditionally, the standard FT and CFL lamps contain a halophosphate phosphor consisting mainly of antimony/manganese-activated calcium oxide (e.g. $Ca_5(PO_4)_3(F,Cl):(Sb,Mn)$) (Chang et al. 2007). In addition, the FT and CFL lamps contain between 5 and 10 mg of mercury to sustain the gas discharge effect. Because of its toxicity, the mercury content is one of the major drawbacks of current state-of-the-art energy-efficient lamps.

The innovation trend towards more energy-efficient fluorescent lamps entails an increasing use of tricolour phosphors, which contain heavy rare earth elements (including La, Gd, Tb and Eu) as well as the transition metal yttrium. The triphosphors consist of red, green and blue-emitting compounds (e.g. Eu^{3+}-activated Y_2O_3 (red); Tb^{3+}-activated $CeMgAl_{11}O_{19}$ (green) and Eu^{2+}-activated $BaMgAl_{10}O_{17}$ (blue)). The concentrations of REE within the phosphors are relatively low (e.g. 1 to 15 mole percent europium in red YEO phosphor; 33 mole percent terbium in green Tb^{3+} quenched phosphors) (Srivastava & Ronda 2003). One fluorescent luminaire system (strip lighting) with two T5 fluorescent tubes, for example, contains a triphosphor with 8.4 g bastnasite (a concentrate consisting of 70% rare earths oxides) (Navigant Consulting 2009). In spite of the relatively low concentrations of REE in modern phosphors, they contribute 7 percent by volume or 32 percent by value to the global consumption of REE (British Geological Survey 2011). The growing use of energy-efficient CFL is believed to entail an increasing demand for heavy REE (Gd, Tb and Eu), which are scarcer than the light REE. This will lead to increasing raw material prices for these elements with prices expected to double by 2015 (Gowing 2011).

The advent of novel lighting technologies will influence the demand for REE-containing phosphors. Solid-state lighting (LED) and organic semiconductors (OLED) expand the range of choices for energy-efficient lighting. Designers and architects can accelerate the transition towards more energy and resource-efficient lighting as they opt for white light-emitting diode (LED) luminaries instead CFL. Phosphor-converted white LEDs (pc-WLEDs) exhibit up to 40 percent higher energy efficiency as compared to CFL. Commercially available pc-WLEDs are set to exceed the luminous efficacy of CFL and may reach 200 lm/W by 2020 (Ye et al. 2010). PC-WLEDs require lower amounts of phosphors because they are smaller than CFL or FT. Nevertheless, this technology will contribute to the consumption of REE and other technology metals, depending on the amount of lighting installed. The solid-state technology is based on the semiconductors gallium nitride or indium gallium nitride. The most common technology to create white light makes use of yellow YAG (yttrium aluminium garnet) phosphor that is excited by blue light. Commonly, these phosphors are doped with REEs, (e.g. Ce, Gd, Eu and Tb).

OLEDs are often regarded as the next generation of energy-efficient lighting technology (Kalyania & Dhobleb 2012). The technology is based on polymer electroluminescence and can be produced by printing very thin layers of a conjugated polymer (e.g. poly(p-phenylene vinylene) on glass sheets or plastic film. Various semiconductive polymers have been investigated for use in OLEDs. Highly efficient OLEDs deploy phosphorescent complex molecules to achieve internal quantum efficiencies close to 100%. These complexes are often composed of an organic host material that contains critical metals, such as iridium, platinum or terbium (Adachi et al. 2001, Chen, Z., et al. 2009). Moreover, the OLEDs contain indium in form of ITO transparent anode material. The active layers and the electrodes are made of thin films (100 nm thickness). The quantity of critical metals used per OLED module is very low.

The innovation trend towards white LED or OLED lighting is not a-priori a viable strategy for designing out critical elements. The consumption of these materials will depend on factors that are influenced by product design and user behaviour. Total material consumption is determined by the useful lives of products and their replacement rates in particular. There is a tendency towards the use of new lighting technologies for disposable products because LED (and in the future OLED) are cheap thanks to mass production. Moreover, there is a trend in product design of applying light sources to products that were not previously illuminated, such as clothing. Prototypes of photonic textiles with textile-integrated LED (e.g. the Galaxy Dress) provide an impression of possible future mainstream products with short lifecycles (Seymour 2010). Future technological progress will allow for the direct application of OLED at the fibre level (Mattana 2011). According to the prevailing views in the product design community, these technologies are destined for future proliferation in the fashion market. In this case, one can expect rebound effects that may lead to an increase in the consumption of technology metals in spite of their minute concentrations in individual products.

7.8. References

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CHAPTER 8

Critical Materials: a Reason for Sustainable Education of Industrial Designers and Engineers

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8.1. Introduction

Numerous publications have documented that the introduction of the concept of sustainable development in the curriculum at technical universities is proving successful (Boks et al. 2006; Fisk and Ahearn 2006; Woodruff 2006; Holmberg et al., 2008; Filipkowski 2011, inter alia). Scholars at the Delft University of Technology (TU Delft), for instance, are conversant with integrating sustainable development topics in design and engineering courses (Boks and Diehl 2006; Kamp 2006). Their experiences suggest that teaching students "*to see the greater perspective*" is a crucial aspect in the curricula (Peet and Mulder 2004, p.280). Sustainability is characterized by complex and multidimensional phenomena, so called "wicked problems" (Coyne 2005; Melles 2008). Wicked problems often entail long-term implications and non-linear behaviour (Lourdel 2005; Kates 2001). They also have a political/societal dimension, which "*can not be solved by the mere application of technical/scientific methods*" (Ehrenfeld 2008 p.167). Thus, designers and engineers should learn to develop sustainable solutions under conditions of uncertainty, for instance by considering the risks of novel technologies before detailed quantitative evidence about those risks is established (Gattie et al. 2011).

Recently, a well-known sustainability issue has gained new impetus: the depletion of mineral resources. Disruptions in the industrial supply of rare earth elements (REE) and other technology metals have lead to concern over the limits in the future availability of critical raw materials (Angerer et al. 2009; Lifton 2009). The attribute 'critical' refers to the high supply insecurity (scarcity) of certain substances in combination with a high economic and technological importance thereof (European Commission 2010). Critical elements are key constituents of modern technologies as they allow for the design of highly efficient products that offer sophisticated functions.

Many renewable energy technologies (such as wind energy, photovoltaic energy, and electric mobility) are dependent on critical materials. The issue has recently moved more into the public domain as the industrial availability of certain REE has become tight. This has led to warnings that materials criticality can present severe risks to society's welfare and prosperity. Also, the extraction, use and disposal of critical materials cause substantial environmental and societal impacts. Hence, the issue of critical materials is highly relevant for sustainable development (Tilton 2003; World Resources Forum 2009).

It appears that materials criticality could be satisfactorily addressed through teaching a number of well-known sustainable design principles (Glavic and Lukman 2007; Fiksel 2009; Bovea and Pérez-Belis 2012): minimization of resource usage, design for reuse/recycling, and/or use of renewable resources. These sustainable design principles, however, ignore the critical materials as they represent less than 0.2% of global materials production (Lifton 2011). The current principles have a focus on tangible materials (steel, plastics, aluminium, etc.). Most critical materials, however, are embedded and dispersed (i.e. in coatings, alloys) and this makes them intangible within existing redesign approaches. For example, taking the approach of minimization of resource usage: when applied to steel, using 20% less in a product might work well. Using 20% less of an alloying element in a material significantly changes the material performance (Wouters and Bol 2009). Another example is recycling. Regaining critical materials from waste products has proven to be extremely difficult. Established recycling technologies are often insufficient to recover critical metals from electronic waste (Chancerel et al. 2009). Today, a big share of electronic high-tech products, containing critical elements, is disposed of without recycling because waste collection and recycling rates are low in most countries (Schluep et al. 2009).

Rigorous application of sustainable design principles, in the way they are currently framed, will even increase the use of critical elements. They are indispensable constituents of those high-tech materials that are needed to make things lighter, smarter, and more efficient. This is an interesting and perhaps unrealized rebound effect of the application of the well-known sustainable design principles. It follows that the industrial designers and engineers should pay more attention to critical raw materials, for instance, through further developing sustainable design solutions or by finding ways to 'design critical materials out' of products. Adjusting the curriculum in a forward-looking manner is a crucial part of the mission of higher education establishments.

The objective of this paper is to convince educators in the design and engineering disciplines to regard materials criticality as a significant driver in sustainability education. The paper gives an overview of the different dimensions of materials criticality and discusses the strategic, practical and collaborative competencies industrial designers and engineers need. The recommendations put forward in this paper are based on discussions with educators and industrial designers at the TU Delft (The Netherlands). This paper opens up this discussion for a wider community of sustainability educators in industrial design/engineering.

8.2. The material base of technology

Mineral resources are extracted from the earth's lithosphere to build and operate our society's technological infrastructures. Almost all metals and semi-metals populating the periodic table of elements have technical applications. In particular the so-called "*technology metals*"

(Lifton 2009), a heterogeneous group of chemical elements, that have become essential for progress in science and technology (Buchert et al. 2009; Angerer 2009). Technology metals allow for the design of highly effective functional components (e.g. strong permanent magnets). Eliminating or replacing these can be done, but often at the cost of lower efficiency and less competitive cost-benefit ratios.

Industries need a reliable supply of technology metals (Angerer 2009). Supply shortages may constrain the development of low carbon energy technologies such as thin film solar cells, wind turbines, and fuel cells (Andersson 2001; Buchert et al. 2009). The demand for technology metals is expected to increase considerably for the following reasons:

- Continued growth of emerging economies (Kooroshy et al. 2010).
- Increasing competition among technology sectors (Angerer 2009).
- Escalating resource consumption caused by decreasing product life spans. High-tech products are replaced by new ones long before they cease to work, an effect that is known as virtual wear and tear (Cooper 2004).
- Lack of a recycling infrastructure for most technology metals (Schüler et al. 2011).

More resources have been consumed, over the last 50 years, than in any other time in history (EPA 2009). Technology metals are non-renewable resources and extracting them inevitably results in depletion. Continuing growth in demand will have to be met by mining at more remote sites and by extracting metals from lower-grade minerals (Kooroshy et al. 2010). Most technology metals are geologically scarce and there is a mismatch between known reserves and expected increase in demand. This geological scarcity can have different causes: some elements, such as rare earth elements, are found in unique mineral deposits that are accessible for profitable mining in only a few countries (e.g. China). Other elements can only be extracted as by-products from refinement processes of base metals. This is true for indium (extracted from zinc), or the platinum group metals (extracted from copper). Production can only be increased if demand for the base metals increases (Verhoef et al. 2004). Other elements (for instance germanium) occur in such low concentrations that profitable extraction is bounded by energy and technological barriers. Therefore, rapid increases in the supply of technology metals is not easy in short-term.

Mineral mining is known for its environmental impacts including disruption and pollution of vulnerable eco-systems, such as the deep sea and the Arctic (Glaister and Mudd 2010; MMSD 2001; Richards 2006). The primary production of most metals is energy intensive and causes large CO2 emissions per mass unit produced (Norgate et al. 2010). Moreover, the social impacts of mineral mining can be severe, in particular for less economically developed countries, whose economies depend heavily on the exploitation of natural resources. The populations of many resource dependant economies suffer from poverty because of social inequality, corruption, and insufficient environmental and social regulation. Under such circumstances, the exploitation of rich natural resources can entail civil insecurity, political instability, or even civil war (MMSD 2002; Le Billon 2003). Artisanal coltan mining, for instance, plays a notorious role in armed conflicts that have affected the eastern Kivu region of Central Africa

(Bleischwitz et al. 2012). The mineral is one important source of tantalum, a scarce element that is indispensable for the production of advanced consumer electronics. Future generations may increasingly be under pressure to sacrifice biotic and social capital (unpolluted environment, healthy marine ecosystems and public health) in order to acquire the remaining abiotic resources. These assets are the opportunity costs of resource exploration and mining (Tilton 2003).

The opportunity costs may be a limiting factor for increasing supply with critical materials in future. The ensuing supply tightness may result in significant difficulties for industries following business-as-usual avenues of technological innovation (i.e. creating more function by using more sophisticated materials).

8.3. Stakeholder perspectives on materials

A growing number of stakeholders in governments, academia and business express concerns over the criticality of materials. This high-tech industry has encountered a reduction in available critical materials (Corfield 2010). Kooroshy et al. (2010) underpin the vulnerability of high-tech economies against acute supply disruption as it can constrain technological progress.

The European Parliament recognises that "*the EU is the world region that outsources the biggest part of resource extraction*" (Bleischwitz et al. 2008 p.6). European industry is increasing its dependence on materials supply from other regions of the world. Materials criticality is understood as a "*subtle, but further reaching*" risk for the European economy. A consultation report of the European Commission acknowledges that raw materials play an essential role in the EU economy (European Commission 2010). The criticality of fourteen raw materials is characterized by their high economic importance and their high relative supply risk (Figure 8-1).

Recommendations fall within two major domains: 1) improving the knowledge base and 2) improving access to primary resources. The recommendations quoted below appear relevant for engineers and industrial designers (European Commission 2010):

- "Encourage more research into life-cycle assessments for raw materials and their products on a cradle-to-grave basis."
- "*Analyse the impact of emerging technologies on demand for raw materials.*"
- "*Improve the overall material efficiency of critical raw materials,*" by "*minimising the raw material used to obtain a specific product function*" and "*substitution of potentially critical raw materials by less critical ones.*"
- Recycling of critical materials from end-of-life products must become more efficient. This can be achieved by "*promoting research on system optimisation and recycling of technically-challenging products and substances.*"

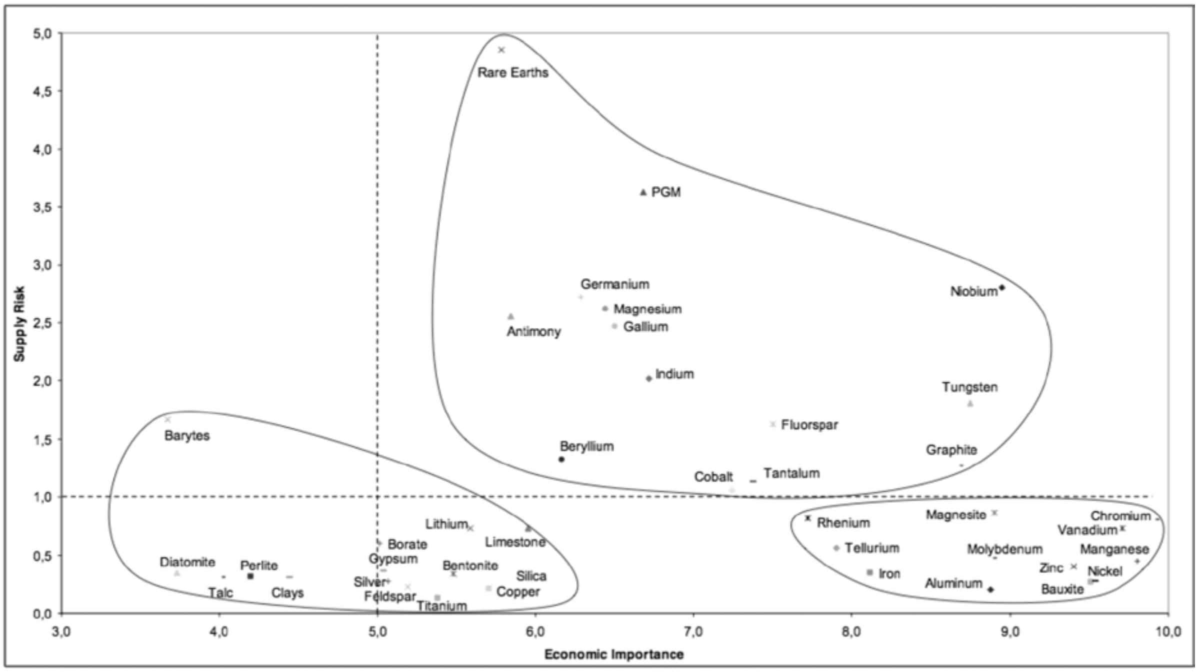

Figure 8-1: Critical raw materials for the European economy. Materials are considered critical (top right cluster) if their relative supply risk is above average (score 1 and higher) and their relative economic importance scores between 5 (medium) and 10 (very high). The scoring metric is based on an aggregated set of supply risk criteria, including the country-specific vendor concentration as well as the substitution and recycling potential of the respective materials. (European Commission 2010)

The US Environmental Protection Agency (EPA) calls for sustainable management of materials and stresses that business-as-usual cannot continue because the "*rapid rise in material use has led to serious environmental effects such as habitat destruction, biodiversity loss, overly stressed fisheries, and desertification*" (EPA 2009 p.ii). EPA recommends careful industrial design as a strategy to reduce the consumption of virgin materials. Sustainable life-cycle management and reuse of materials can help "*to fulfil our human needs and prosper while using less material, reducing toxins and recovering more*" (EPA 2009). Industrial designers are encouraged to note the following recommendations:

- "*Initiate demonstration projects on a few well-chosen materials and products to show the value of integrated materials management strategies*". "*Recognize and support champions*" of sustainable materials management approaches.
- Build capacity to support life-cycle materials management (e.g. data and decision tools), including necessary research.
- Engage in a broad public dialogue on life-cycle materials management to "*create public awareness of the environmental consequences of material and product choices.*"
- Promote greener products, product stewardship, and product-to-service transformations.

UNEP, the United Nations Environment Programme, has prioritized the materials criticality problem. Future sustainable technologies are found to be critically dependent on "*green minor metals*", a range of elements comprising indium, germanium, tantalum, platinum group metals, tellurium, cobalt, lithium, gallium, and rare earths. A short-term scarcity risk exists for the elements gallium, tellurium, and indium. The report suggests increasing research and development to encourage recycling of these critical materials and underscores the importance of enhanced know-how transfer and international knowledge cooperation (Buchert et al. 2009).

8.4. Discussion

In order to prevent future overshoot in demand for critical raw materials, it would appear sensible to address limits in raw material and energy supply through product innovation (Richards 2006; Davidson et al. 2010). Industrial designers and engineers can have a profound influence on the demand side for critical elements. Although they can by no means single-handedly solve the materials criticality problem they can influence how products are produced, used and recycled throughout their life cycles.

Industrial designers can endeavour to design-out the usage of critical materials in products. Possible strategies encompass technological innovation as well as change of product usage patterns by design. Dematerialisation, for instance, is a sustainable design strategy to fulfil user demands in less material and energy intensive ways (Ljungberg 2007). New developments in nanotechnology hold great promises to miniaturise certain functional components of products and to increase the overall resource efficiency of technical systems or processes (Som et al. 2011). Examples are nano-coatings of surfaces and quantum-dot based lighting and display technology (Steinfeldt at al. 2007). However, some scepticism has been voiced over whether the high expectations on the benefits of nano-products hold true (Fiedeler 2008; Nikulainen and Palmberg 2010). Designers can cooperate with material scientists to showcase how realistic the substitution of nano-materials for critical elements is in practice. In doing so, the opportunities and risks of applying engineered nano-materials in products must be carefully assessed to avoid potentially adverse side effects.

Another possibility is making emotionally durable designs for longer lasting products, reducing the loss of critical elements in difficult-to-recycle waste streams (Richards 2006). Finally, implementing design for recycling in the development of products can help in keeping critical materials longer in the cycle of value creation.

The community of industrial designers and engineers is currently largely unaware of the emerging challenge of critical materials. The issue appears peripheral to the core business of product developers, leading them to underrate the supply risks (Richards 2006). Materials criticality has also been given little attention during the higher education of those professionals that may have to cope with the problem in future. Davidson et al. (2010) report that in the U.S. "*currently graduating engineers may not realize the constraints of limited resources and limited sinks for waste products as they enter the workforce*". The same can be said about graduates from European technical universities. Brehmer (2010) observed in a survey with design and engineering companies that most of them are hardly aware of critical materials.

In conversations and interviews with these professionals, it was noticeable that design engineers working for enterprises face difficulties in taking informed decisions in favour of sustainable design. They have difficulties to find, to access, and to interpret extant knowledge on the criticality of materials. Usually, they lack information on what substances are contained in intermediate materials and sub-assemblies purchased from upstream suppliers. Moreover, they often lack overview of the fate of critical materials throughout the downstream product life cycle (use phase and end-of-life phase). Alternative technical solutions that would fulfil the same function in a more sustainable manner, i.e. using less critical materials or new technologies (such as engineered nano-materials) are therefore not readily taken into account.

Hence, a debate among the higher education community appears overdue on how to address the materials criticality problem adequately in the curriculum of design-engineering programmes. The current student cohort in industrial design and engineering courses is likely to encounter shortages in availability of technology materials sooner or later in their professional careers. Bremer and López-Franco (2006) emphasize that "*the alumni will become the decision-makers in their homes, industries,*" and can act as "*agents of change by knowing the impact of their actions (and inactions) on the environment, society, and future generations*". Thus, it is key to make them aware of the fact that design decisions can have substantial impacts on society's demand for critical materials.

8.4.1. Implications for the curriculum of higher education

Design engineering education is challenged to train students with analytical skills necessary to conceive solutions for problems that are ill-structured and scientifically uncertain (Gattie et al. 2011). Material criticality represents such a case when teaching sustainability in higher education. The concept of sustainable development provides the appropriate context for framing the complexity of the material criticality phenomenon. The issue should, however, by no means override the holistic approach of sustainable education. To the contrary, educators should cultivate an attitude among future technology developers to take the environmental, political, and socio-economic context into account when they make engineering decisions. Materials criticality can also be used in research classes as a basis for students to develop possible future research.

Boks and Diehl (2006) point out that design-engineering students in BSc courses appreciate case-specific input when discussing sustainability in product design. Widening the scope of sustainability in learning assignments inspires both students and teaching staff to assess the design decisions against various aspects of sustainability (Segalàs et al. 2010). Along the same line of arguments it appears that materials criticality brings up a number of concrete sustainability issues, worthy to reflect upon during a learning exercise. These issues comprise not only environmental aspects but also the impacts of design decisions from a business perspective, such as future supply risks, return-on-investment and strategic innovation needs. Moreover, the students ought to be made aware of the societal implications of materials criticality (Köhler, 2012). Industrial designers and engineers have a collective responsibility to conceive sustainable solution strategies because they determine the demand for raw materials through the design of products. Designers are also trendsetters for the societal adoption of these products and this influences the fate of critical materials contained therein (ibid).

The authors' recent experiences drawn from MSc-level Life Cycle Engineering & Design course at TU Delft suggest that some of the students embrace the challenge of materials criticality. Duwel et al. (2011), for instance, express their insights gained from the master-level course “Life Cycle Engineering and Design”: “*The project made us realize the responsibility we have in designing products and selecting components and materials, but it also showed us that there are a lot of hurdles to overcome. There is a lot of work to do to persuade users, companies and other designers to address material scarcity*.” In the MSc graduation project of Brehmer (2010), the researcher assessed the awareness of companies regarding critical materials within the product development process. Brehmer concludes that materials criticality “*is a problem that can be solved. It does, however, require smart thinking, the willingness to change, good collaboration within and between firms in the value chain, and planning ahead.*” (ibid, p.158). Figure 8-2 gives an overview of suggested actions to mitigate or prevent the critical materials risk.

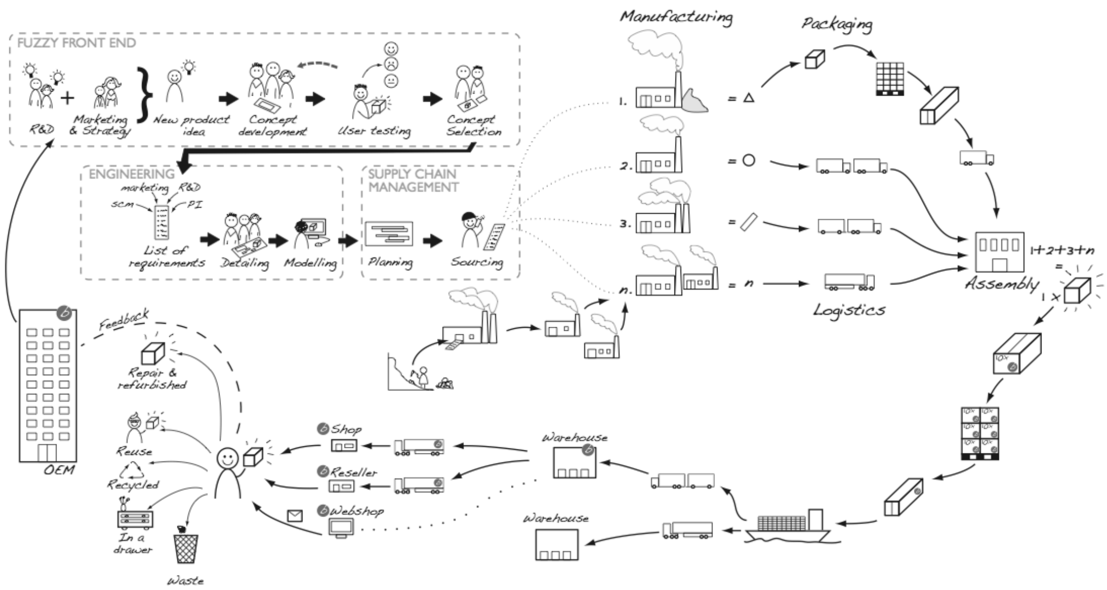

Figure 8-2: Conceptual framework for the analysis of influencing factors of critical raw materials consumption throughout a generic product development process and subsequent product life cycle. (Brehmer 2010)

It follows from the above said that future employees should be equipped with capacities and skills to thrive under circumstances of constrained material choices. Therefore, it appears necessary to train design and engineering students with certain skills in life-cycle thinking and policy analysis. With view at the recommendations of eminent stakeholders (summarised in section 8.3.) and taking into account experiences with teaching sustainability (Boks and Diehl, 2006; Brundiers et al. 2010; Gattie et al. 2011) the following aspects have been given weight in the curriculum of design engineering courses at TU Delft:

- Forming an understanding of the energy and materials base of modern technology, including a grasp of cause-effect relationships regarding the sustainability impacts of design decisions. That helps to understand the interrelations between the design of products, consumption patterns, product end-of-life treatment; and the sustainability impacts.
- The competency to make sustainable design decisions under conditions of incomplete knowledge regarding material supply risks.

- The ability to design technical and functional alternatives as an approach to identify and implement materials substitution potentials.
- Awareness of basic policy trends in order to gain an understanding of stakeholder interests and to recognise future regulations. An awareness of the wider social and political landscape, with respect to technological innovation, is a prerequisite to be able to create new technologies and products that are socially acceptable.

The above suggestions give prominence to the recommendations of major policy bodies regarding know-how transfer and capacity building (Buchert et al. 2009, EPA 2009; European Commission 2010). The following section elaborates ideas on how the educators themselves may develop their own knowledge, allowing the materials criticality issues to be brought to the attention of students.

8.4.2. Implementation of solutions in education

The ideas below outline how to support students in accessing knowledge on critical materials and help them learning how to interpret this information in advance of sustainable materials management.

From the observations it can be concluded that design and engineering professionals can benefit from knowledge support (Davidson et al. 2010). Appropriate methods and tools, which make complex information accessible to them in an easy manner, can assist them to overcome the prevailing knowledge gap. One possibility to help achieve this is setting up an open access knowledge repository system that hosts information such as:

- Application areas of critical elements and their functions.
- Inventories of products components that rely on critical materials.
- Recyclability indices and actual recycling rates of critical materials from waste.
- Compendium of substitution potentials on the level of materials or product components.
- Design guidelines for substitution or elimination of critical materials.

Upgrading established engineering databases and material selection guides such as the Granta Cambridge Engineering Selector (CES) with materials criticality related data would greatly support the profession of industrial design engineers as a whole.

Moreover, there is a need for building capacities in effective implementation of sustainable design tools (Design for Sustainability - DfS) and methods (such as Life Cycle Assessment - LCA) (Tingström and Karlsson 2006). DfS-methods can be used as a building block for creating a resource-aware design framework but they need to be customized to the emerging problem of materials criticality.

8.5. Conclusion

This paper illustrated that materials criticality is a relevant problem that deserves attention in design and engineering disciplines, which are proponents of technological innovation. Design-engineering graduates should start their professional lives endowed with a sense of responsibility and having a pro-active attitude regarding materials criticality. To foster the sustainable use of critical materials it is key to train tomorrow’s design engineers with skills in gathering and interpreting complex and sometimes ambiguous information related to the material resources they work with. The TU Delft, with its experience in sustainability in higher education, has engaged with this challenge and is in the process of developing strategies for resource-aware product design. Course instructors challenge design and engineering students to analyse what implications the impending scarcity of critical technology material can have from the perspectives of engineering and sustainability. A crucial element of such an approach is to provide ongoing technology developers with skills and methods to tackle the challenge.

Students need to acquire competencies to address 'wicked problems' under conditions of uncertainty and to think beyond the established principles and guidelines of sustainability. Some of them embrace the intriguing challenge that comes with the material scarcity phenomenon. The higher education system should encourage these individuals to engage with sustainable innovation and support them to become agents of change.

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CHAPTER 9

Conclusions

The starting point of this research was the observation that emerging technologies can entail undesired side effects on environmental sustainability. In many cases, adverse environmental impacts of production and consumption have been observed after high-tech products had proliferated. The life cycle wide environmental impacts of products are, for the most part, determined in the design stage. It was therefore considered relevant to intervene in the innovation process of emerging technologies to prevent the environmental risks of next generations of high-tech products. It was assumed that implementing eco-design in an anticipatory manner, that is ex ante to the market introduction of new technologies might help in preventing environmental risks before they materialise at large scale.

Through studying the innovation process of smart textiles it was explored how the developers of smart textiles can prevent future environmental impacts. The following sections provide a synopsis of the findings in response to the research questions introduced in section 1.6.

9.1. Answers to the central research question

The central research question of this dissertation was: **"How can environmental risks of emerging technologies be prevented at an early stage of the innovation process?**"

The research reported in this dissertation has shown that the technological innovation of emerging technologies, such as smart textiles, may result in environmental side effects, including the consumption rates of scarce material and energy resources as well as the generation of large amounts of waste. The prospective impacts of smart textiles may add to the familiar consequences of environmental sustainability that result from the large-scale production and consumption of products. In addition, new and unexpected side effects on environmental health and safety may result from the application of emerging technologies, e.g. nanotechnology, in consumer products. But there is uncertainty about the order of magnitude and the exact nature of environmental impacts in future. From today's viewpoint, these risks are not thought to entail catastrophic environmental damage in the short term. However, they can aggravate environmental damages in the long run.

The prospective environmental impacts of smart textiles have the potential to jeopardise the objectives of sustainable innovation policies that aim at a greener and more resource efficient economy (EC, 2010). It is therefore reasonable to consider the familiar and the unexpected side effects as possible deviations from the objectives of sustainable innovation, which refers to the notion of risk. Risks should be mitigated in the framework of risk management. This dissertation has presented approaches to implement eco-design and Life Cycle Assessment as a risk prevention measures concurrent to the technological innovation process.

For reasons explained in sections 1.4 and 7.5, the design stage holds the most promising opportunities to prevent environmental risks by means of environmentally conscious product design. However, the uncertainty and the complexity of relevant factors hamper the recognition and the mitigation of intangible risks. The chapters 7 and 8 delineated material scarcity as an example of an intangible risk. It is therefore suggested to treat the intangible environmental risks of emerging technologies in accordance to the precautionary principle.

From this background, the dissertation elaborated strategies for precautionary risk mitigation. They purpose to bridge the gap between insufficient risk appraisal and the opportunity to prevent them (see figure 1-5: p23). Three overarching approaches are recommended as means to install risk prevention measures at an early stage of the innovation process:

1. Implementing anticipatory eco-design heuristics based on Life Cycle Assessment concurrent to the technology innovation process.
2. Developing the education and skills of industrial designers and engineers to enable them to work out and implement concrete eco-design measures.
3. Raising the risk awareness of industrial designers and engineers and forming attitudes to counteract risks proactively.

These strategies are coherent to the risk treatment strategies suggested in the risk management framework ISO 31000 (section 1.4.1). Eco-design can help to remove the risk source (e.g. the content of hazardous substances in products) and to change the likelihood and the consequences of adverse impacts (e.g. making save products that are long-lasting and recyclable). The simplified Life Cycle Assessment (LCA) method, proposed in section 6.7 purposes to ease informed decision making during the design process of smart textiles in order to reduce risks. It should support environmentally conscious choices at the product development stage.

Apart from the risk mitigation strategies proposed above, it is suggested that technology developers and product designers scrutinise the mega-trend of technological convergence from an environmental perspective. To avoid unsustainable lock-in effects it is important to constantly reconsider the possible benefits of smart everyday objects against the possible risks. The risk management framework (ISO 31000:2009) leaves two radical alternatives in cases where the above mentioned risk prevention strategies fail to mitigate the risk: A) the risk-avoidance strategy and B) the risk-taking strategy. While B) is the business-as-usual option in technological innovation it might be wise to take strategy A) into account and "*not to start or continue with the activity that gives rise to the risk*". For instance, the design vision of seamless integration/combination of electronics and textiles should be judged with a view of the resulting waste problem. If the decision was in favour of a risk-taking strategy then sustainable development ethics would impose a high measure on the benefits to be gained by engaging in such risks (section 7.4&5). This means, the innovation process ought to yield valuable and durable forms of social capital, which are really worth the long-term value of the natural capital at stake. This judgement can only be case specific and must be open to review when new insights about the risk become available.

9.2. Synopsis of the research results

9.2.1. Answers to research question Q1

The first research question related to the case study on smart textiles was: “What are the environmentally relevant properties of smart textiles and what environmental risks can be expected to emerge during their product life cycle?”

The risk analysis, undertaken to answer this research question, was based on technology assessment (chapters 2, 3, and 7.7), design inclusive research (chapter 5) as well as life cycle assessment (section 6.6).

It was first investigated which environmental impacts could result from the technological mega-trend of smart everyday objects (pervasive computing). It was shown that the widespread production and consumption of smart technologies will bring about both, additional loads on (first-order impacts) and benefits to (second-order impacts), the environment. The everyday use of smart objects with embedded electronic components may cause additional energy consumption because these products are usually electrically powered. A Life Cycle Assessment (LCA) of a smart textile product for Ambient Assisted Living (section 6.6) suggests that the system’s electricity consumption during its use phase is the most relevant environmental aspect. The concept of integrating energy-using electronic devices into previously passive everyday objects is a contributing factor to the further increase of energy consumption rates in total.

Moreover, the mass production of ICT is known for its immense consumption rates of critical raw materials and the production of electronic textiles is likely to amplify the demand. The production and consumption of high-tech devices is a cause of increasing industrial demand for critical raw materials. There are warning signs about an impending scarcity of certain technology metals that constitute the material base of modern technology. The case studies in chapter 7 illustrate the risk of material scarcity to hold back future innovations of high performance technologies, especially those considered key enabling technologies. However, this risk is often underrated in the pursuit of technological progress, as it appears rather intangible due to the complexity of influencing factors. Critical materials may be lost on the end of the life cycles of e-textiles because they are dispersed in large amounts of electronic waste that is hidden in textile objects. The expected difficulties in recycling critical materials contained in smart textiles will aggravate the phenomenon of material scarcity.

The mass application of e-textiles can result in a considerable new e-waste stream, which poses new disposal problems with regard to technical, economic, and legal aspects (see chapter 3). In particular the innovation trend towards seamless integration or combination of electronics and textiles gives raise to concern over possible problems in end-of-life treatment. The established disposal and recycling schemes for e-waste and old textiles are not capable to process such a blended feedstock, containing tightly amalgamated electronic and textile materials. It is expected that old e-textiles will be difficult to recycle because valuable materials are dispersed in large amounts of heterogeneous textile waste. Unmitigated end-of-life problems will eventually result in environmental pollution and a loss of critical materials in waste. In addition, electronic components in e-textiles can contain problematic substances and it cannot be ruled out that they that act as contaminants in the recycling of textile materials. They could be released during recycling processes and cause new environmental and health problems. This entails also the risk of cross-contamination and could render the recycling of textiles and electronic materials less profitable. It would remove the economic incentive for sustainable end-of-life management of high-tech waste. In future, it might come to transboundary movements of old e-textiles towards developing countries, similar to certain illicit practices observed with contemporary e-waste exports.

These first-order environmental impacts are to be evaluated against the second-order effects. Smart products could theoretically help in optimising the eco-efficiency of numerous physical products and activities and processes carried out in daily life, such as personal travel, space heating, lighting etc. Many of these material and energy intensive activities could be replaced, or least optimised, by signal processing and data interconnection, which are in the heart of smart functions. Thus, smart textiles could aid the idea of dematerialization. The potential environmental benefits from such second-order effects are considerable and can outweigh the first-order effects. For instance, the LCA reported in section 6.6 indicates that the use of smart technologies has the potential for energy saving in space heating and lighting of buildings. However, that possibility holds true only under the condition that smart products are purposefully designed and applied for that purpose. If not, they may even result in an increase of the total material and energy consumption. The increasing demand for smart products and services can counterbalance any potential efficiency gains of dematerialisation effects.

Such rebound effects may also occur if a more efficient technology enables significant savings of time and money (third-order effects). Consumers might feel encouraged to spend the saved time and money for new consumption activities that would then increase the total turnover of materials and energy in society. In addition, the rapid innovation cycles of the ICT sector may quickly depreciate the value of products in the consumer's eye. Fleeting design trends of consumer goods can lead to progressive obsolescence of smart objects; a virtual wear out effect that is typical for electronic high-tech products. The phenomenon causes products to be more frequently replaced with new ones. This intensifies the consumption rates of non-renewable resources and increases the amount of waste.

In summary, the research findings of this technology assessment underscore that the design of emerging technologies has profound influence of the I = PAT equation explained in section 1.1. (p.9). The results indicate that some of the expected features of smart textiles may contribute to increasing environmental pressures on the planet as it influences the factors A (consumption of products & services per person) as well as the factor T (technology efficiency, i.e. environmental impacts per product). The anticipated properties of smart textiles resemble the side effects of contemporary high-tech products, which are known to cause significant environmental impacts globally. These risks encompass potential adverse side effects of production and consumption activities with these products over their whole product life cycle. E-textiles are not expected to cause unprecedented risks for the environment (chapters 2 & 3) whereas the application of engineered nanoparticles in textiles may inflict unforeseen side effects on environmental health, safety and sustainability (EHS/S) (chapter 4). It is noteworthy that the environmental side effects of e-textiles may materialise under unexpected circumstances (e.g. in recycling processes). Moreover, the human exposure to possible adverse impacts may increase as wearable smart textiles are worn close to the human body.

The possible environmental impacts can be expected to have a relevant order of magnitude because e-textiles, like other visionary concepts of smart products, are set to become a mass application in the future. It is therefore reasonable to evaluate the environmental risks of smart textiles as highly relevant in terms of impact as well as likelihood of occurrence.

9.2.2. Answers to research question Q2

The second research question related to the case study on smart textiles was: "What is the status quo of implementation of environmental risk assessment and risk mitigation in the innovation sector of smart textiles?"

In conjunction with the risk analysis of smart textiles it was also explored how aware the technology developers are in regard to possible risks. The research was undertaken by means of a questionnaire-based survey, telephone interviews, and personal interaction with developers, designers, and entrepreneurs in the field of smart textiles. This section summarises findings from chapters 4, 5, 6, 7, and 8.

The examination of smart textiles resulted in warning signs for possible environmental impacts. However, the current knowledge about the properties and functions of smart textiles is insufficient. The nature and the extent of prospective environmental impacts remain uncertain at the early stage of technology development; a reason to consider the potential environmental impacts as risks. The assessment of these risks is rather intangible because it is impossible to characterise these risks with high confidence.

Throughout the research, it was repeatedly observed that technology developers seem to lack awareness and knowledge about such intangible risks. Many innovators seem to be inattentive to possible adverse side effects because the assessment of such risks is not perceived a priority on the innovators' agenda. Moreover, the developers of smart textiles lack the skills and resources necessary to examine the possible side effects concurrent to the technology innovation process. This is especially true for small businesses. Both, the uncertainties as well as the ambiguity of available knowledge make it difficult for them to comprehend the possible environmental impacts of the products they design.

Materials scarcity and the end-of-life aspects of e-textiles are examples of risks that have been insufficiently scrutinised throughout the innovation process. The findings of this research suggest that the innovators are usually not well aware of these issues and that they feel they are not responsible for implementing risk preventative actions. In several cases, technology developers delegated the responsibility to prevent risks to other actors, such as scientists, consumers, policy makers, the mining & recycling industry, etc. This situation is typical for a business-as-usual mode of technological innovation. In chapter 7 the questions of awareness and responsibility was reviewed from the viewpoint of sustainable development ethics. From the background of the material scarcity phenomenon it was discussed whether preventive actions should be taken today, and by whom, in order to mitigate resource scarcity in the future. There are valid reasons for industrial designers and engineers to create a sense of responsibility for the proactive mitigation of material scarcity. Being protagonists of the innovation system, they have the opportunity to lead the change towards resource-aware technology development. On the base of these arguments, it can be concluded that technology developers ought to become more attentive to the possible adverse side effects of technologies they create. And, they may rethink their own action potential to counteract risks before they manifest themselves in the form of environmental damage. It is therefore advisable to carry out environmental risk assessment at the early stages of product innovation.

LCA is a considered a powerful method to inform the product designer about environmental risks of products – at least for those aspects that have a historical precedence, such as power consumption, hazardous materials and end-of-life treatment of products. LCA can be used to identify the improvement potential and to derive environmentally conscious design options. The examination of the status quo of LCA implementation in SMEs (chapter 6.5) led to the conclusion that LCA is rarely applied in business practice. It was shown that there are barriers impeding the widespread use of LCA as a decision support instrument for product design. The main obstacle is the lack of data about the environmentally relevant properties of smart textiles. Companies and innovators have insufficient resources at their disposal to acquire extensive life cycle inventory data that are needed to conduct comprehensive LCA. In conclusion, a simplified LCA tool could be beneficial for innovators, who engage in the development of smart textiles products.

9.2.2. Answers to research question Q3

The third research question related to the case study on smart textiles was: "How can eco-design be applied at the early stage of smart textile technological development to prevent environmental risks?"

Based on technology assessments, chapters 3 and 4 discuss strategies for the precautionary management of potential end-of-life and EHS/S risks of smart textiles. Chapter 5 outlines risk-preventative eco-design strategies that were elaborated by design-inclusive research in the framework of a focus group workshop. The sections 6.7&8 propose a simplified LCA-to-go approach, which aims at boosting the application of LCA in SMEs at an early stage of the development process of smart textiles. Chapters 7 and 8 propose awareness raising and educational measures as a means to enable industrial designers and engineers to counteract intangible risks.

Eco-design is a recommended strategy for sustainable innovation. It can help in creating sustainable and socially accepted products and minimise the generation of waste in future. But the combination of textile and electronic technologies poses new challenges for eco-design. For instance, the existing design for recycling (DfR) principles for textiles, or electronics, do not match with the properties of the products, when they are combined. It is therefore difficult to apply them in the development process of an emerging technology. This makes it necessary to re-examine the existing eco-design approaches and to develop them further so that they suit the features of the convergence technology. As for the case of smart textiles, three waste preventative eco-design approaches are proposed: 1. Harnessing the inherent advantages of smart materials for sustainable design; 2. Establishing open compatibility standards for the enabling technologies and system components of e-textiles; and 3. Labelling the e-textiles with a unique logo so as to ease their identification in recycling processes.

However, the prospects of DfR to successfully prevent future end-of-life problems should not be overestimated. The recycling of discarded products is hardly more that a technical 'quick fix' to mitigate some of the adverse environmental impacts at the end of life. In practice, the collection and recycling rates of obsolete high-tech products are rather low (particularly the small electronic appliances which escape and are not fed into recycling). Hence, designing recyclable e-textiles does not automatically warrant for effective waste prevention.

Clear regulatory frameworks or standards are necessary to make the implementation of eco-design in the field of emerging technologies feasible. Sending clear signals to industry is seen as an essential policy instrument for sustainable innovation. Therefore, the legislature should introduce anticipatory mechanisms in the regulatory framework foster the proactive implementation of eco-design principles in technological innovations. One action area on the European level is the Integrated Product Policy (EC, 2003). The Eco-design directive (EC, 2009a), for instance, should be recast to accommodate emerging product groups that do not (yet) fulfil the currently applicable relevance criteria. Specifically, emerging technologies have no "*significant volume of sales and trade*" (Article 15.2(a)), "*a significant environmental impact*" (Article 15.2(b)) is hard to demonstrate, and a "*significant potential for improvement*" (Article 15.2(c)) is difficult to present. With having the precautionary principle in mind, the regulatory hurdle for the application of eco-design in innovative sectors should be lowered. Furthermore, it is advisable to insert electronic textiles list of product categories considered by the WEEE directive (EC, 2012).

With regard to more fundamental risks, such as material scarcity, it must be kept in mind that the real challenge is in overcoming systemic causes of the waste problem. One important aspect is the progressive obsolescence of high-tech products. The phenomenon has its roots in the throwaway habits of society. The high replacement frequency of high-tech devices entails both, depletion of scarce raw materials and their subsequent squandering in the form of difficult-to-recycle e-waste. Hence, it is argued that technology developers ought to adopt life-cycle thinking when they design new products.

Feeding LCA-based knowledge into the development process of an emerging technology is recommended as a risk prevention strategy. LCA ought to be used as a tool for informed decision-making much earlier than it is usually done at present. In order to change the status quo in regard to (non)-application of LCA in the technological development process it is necessary to make the method easier to apply in business practice. From the explorative observations in the smart textile innovation process it can be concluded that product designers do not necessarily need robust LCA results for decision support at the early design stage. Rather, they often rely on heuristics, that is, rules of thumb that guide the designers' thinking in a sustainable direction. Hence, it is proposed to compile LCA-based eco-profiles of typical smart textiles as a fist step towards a simplified LCA approach. The LCA-to-go approach proposed in section 6.8 aims at making LCA-based knowledge accessible to SMEs who pioneer the commercial development of smart textiles. The LCA-to-go tool[43] will help to identify the environmental improvement potential of smart textiles without the need to conduct a full LCA. It's purpose is supporting the adoption of eco-design at the fuzzy front end of the smart textiles innovation process.

Section 6.4 illustrates some aspects of existing LCA tools that deserve improvements beyond the state of the art. Important aspects are easy guidance for novice LCA practitioners and general user friendliness through an intuitive design of the graphical user interface of LCA software. Moreover, there is a need to provide an easily accessible (open source) and comprehensive database of secondary LCI data of typical materials, components, and manufacturing processes of smart textiles.

One drawback of the LCA methodology is its lack of sensitivity for emerging risks, such as the potential EHS/S effects of nano-materials. Also the impending scarcity of certain technology metals is not adequately accounted for in LCA. This shortcoming of LCA makes it necessary for industrial designers and engineers cultivating a complementary knowledge to be able to appraise such wicked problems as material scarcity. It is important to train future design and engineering professionals to be receptive to early warnings on emerging risks. Those, who develop new technologies, should be trained to apply a systems perspective to the process of technology innovation. The chapter 8 outlines ideas on how to weave the topic into existing educational programmes of future technology developers.

9.3. References

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[43] The LCA-to-go software tool is going to be created by a member of the LCA-to-go consortium, based on the methodological concept outlined in section 6.7.

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List of Tables

List of Figures

Abbreviations

Ag	Silver
Al	Aluminium
ALARP	As low as reasonably practicable (a principle)
Au	Gold
B2B	Business to Business
BAU	Business-as-usual
BSc	Bachelor of Science
C2C	Cradle to Cradle
CED	Cumulative Energy Demand (an LCA based indicator)
CD-RW	Compact Disc-ReWritable
CE	European Conformity
CEN	European Committee for Standardization
CEO	Chief executive officer
CFL	Compact fluorescent lamps
CNT	Carbon nanotubes
CO2	Carbon dioxide
Cr6+	Hexavalent chromium
CRT	Cathode ray tubes
CTO	Chief technology officer
Cu	Copper
DfE	Design for Environment
DfR	Design for Recycling
DNA	Deoxyribonucleic acid
DQI	Data Quality Indicator
DRAM	Dynamic random-access memory
EA	Environmental assessment study
ECG	Electrocardiograph
eco-design	Environmentally conscious design
EEA	European Environment Agency
EEE	Electrical and Electronic Equipment
EHS/S	Environment, health & safety and sustainability
EIA	Environmental Impact Assessment
EIP	Ecoindicator Points
ELCD	European Life Cycle Database
ENP	Engineered nanoparticles
EMS	Environmental Management System
EOL	End of life (disposal phase of a product)
EPA	Environmental Protection Administration
EPC	Electronic Product Code
EPD	Environmental Product Declaration
EPR	Extended producer responsibility

ErP	ErP Ecodesign Directive 2009/125/EC on Energy related Products
e-textiles	Electronic textiles
EU	European Union
EuP	Energy-using Products
EVR	Eco costs/value ratio
e-waste	Electronic waste
FEI	Fuzzy front end of product innovation
FMEA	Failure modes and effects analysis
FP7	Seventh Framework Programme of the European Union
FT	Fluorescent tubes
GaAs	Gallium arsenide
GPS	Global Positioning System
GSM	Global System for Mobile Communications
GUI	Graphical User Interface
GWh	Giga watt hour (an unit of energy)
high-tech	High-technology (most advanced technology currently available)
ICT	Information and Communication Technologies
IPP	Integrated product policy
ILCD	International Reference Life Cycle Data System
ISO	International Organisation for Standardisation
ITO	Indium-tin oxide
kg/cap	Kilogram per capita
nano-Ag	Nanosilver
KEPI	Key Environmental Performance Indicator
ktonnes	Kilo tonnes (1000 tonnes) (an unit of weight)
LCA	Lifecycle analysis / life cycle assessment
LCD	Liquid crystal display
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Analysis
LED	Light-emitting diodes
Li-ion	Lithium-ion battery
MB	Megabyte ((an unit of data)
MJ	Mega joule (an unit of energy)
MSc	Master of Science
MSW	Municipal solid waste
n.a.	Not available
NGO	Non-Governmental Organisation
OECD	Organisation for Economic Co-operation and Development
OEM	Original equipment manufacturers
OLED	Organic light-emitting diodes
PAni	Polyaniline
PBB	Poly-brominated biphenyls

PBDE	Polybrominated diphenylether
PCF	Product Carbon Footprint
PCM	Phase change materials
PCR	Product category rules
PDA	Personal Digital Assistant (a small, mobile computer)
PEDOT	Poly(3,4-ethylenedioxythiophene) (a conducting polymer)
PET	Polyethylene terephthalate, (Conventional plastic)
PGM	Platinum group metals
PP	Precautionary principle
PPy	π-Conjugated polymer
PTE	Periodic Table of Elements
PWB	Printed wiring boards
QR	Quick Response codes
QWERTY	Quotes for environmentally weighted recyclability factors
R&D	Research and Development
REACH	Registration, Evaluation, Authorisation and Restriction of Chemical substances, (EU Directive)
REE	Rare earth elements
RFID	Radio frequency identification
RoHS	Directive 2002/95/EC on the Restriction of Hazardous Substances
SEA	Strategic Environmental Assessment
SD	Sustainable development
SIM	Subscriber identity module card
SME	Small and medium enterprises
SWOT	Strengths, Weaknesses, Opportunities, and Threats –analysis
TA	Technology assessment
TV	Television
TWh	Terra watt hour (an unit of energy)
UCTE	Union for the Co-ordination of Transmission of Electricity (refers to the average European electricity mix)
UK	United Kingdom
UMTS	Universal Mobile Telecommunications System
USB	Universal Serial Bus
UV	Ultraviolet light (wavelength of electromagnetic radiation)
Ti	Titanium
WEEE	Waste Electrical and Electronic Equipment
W-LAN	Wireless local area network
WLED	White LEDs
YAG	Yttrium aluminium garnet
YEO	Europium-doped yttria phosphor

Short definitions and terms[44]

Converging technologies: In the context of this dissertation, the term 'converging technologies' is used consistently with the European approach as outlined by Nordmann (2004): "*enabling technologies and knowledge systems that enable each other in the pursuit of a common goal.*"

Cradle-to-grave: A LCA that includes all life cycle phases from resource extraction (cradle) to the end of life (grave) of a product (Guinee et al. 2001).

Cradle-to-gate: A LCA that includes parts of a product life cycle from resource extraction (cradle) to the end of the production value chain (factory gate). The use and end of life phase are excluded (Guinee et al. 2001).

Eco-design: Refers to 'environmentally conscious design' (DfE) or 'Design for Environment' respectively. The term is understood in the sense of the definition of the European ErP directive: "'Ecodesign' means the integration of environmental aspects into product design with the aim of improving the environmental performance of the product throughout its whole life cycle" (EC, 2009).

E-textiles: Electronic textiles are characterised by integration or combinations of textile materials (e.g. cotton, polyester) and electronic components, such as sensors, flexible PCB, and photovoltaic cells. The term 'e-textiles' refers to the hardware and the term 'smart textiles' refers to the function of these products.

EHS/S: Environment, health & safety and sustainability

Emerging Technology: Refers to new technologies that are research and know-how intensive. Harper (2010) provides a preliminary characterisation:
- '*arise from new or the innovative application of existing knowledge'*,
- '*lead to the rapid development of new capabilities*',
- '*significant and long-lasting economic, social, political impacts expected*',
- '*create new opportunities for and challenges to addressing global issues*',
- '*have a disruptive potential to create entire industries*'.

High-tech: High-technology refers to innovative products that are characterised as follows
- high R&D intensity,
- high ratio of R&D/sales revenue,
- high technological uncertainty about products and processes,
- hard to find the technological know-how on the labour market (Calori, 1992).

Industrial designers and engineers: are professionals or scholars who transform product ideas and technological concepts into concrete product development projects. The industrial designer works on form and function of products in order to satisfy the needs of users. Design engineers, on the other hand, focus on the development of technical aspects in the design of

[44] References refer to the list of references at the end of chapter 9

products destined for mass production (Delft Design Guide, 2011). In the smart textiles sector, both specialisations contribute to the technology development process.

Innovation: The conversion process from scientific and technological knowledge (inventions) to economically successful products (Twiss, 1980).

Innovator: In the context of this dissertation, the term 'innovator' refers to entrepreneurial actors in the innovation system. In comparison to technology developers, the innovator acts from a business perspective and focuses at successful commercialisation of smart textiles.

Smart textiles: For the purpose of this study, the term 'smart textiles' is understood as textile products that offer augmented functionality in form of integrated electronic components. The term 'smart textiles' refers to the function and the term 'e-textiles' refers to the hardware of these products. Smartness is defined as the product's capability to sense external stimuli and to respond actively in an engineered manner.

Pervasive Computing: Synonym to Ubiquitous Computing, denotes the idea of microelectronics that is unobtrusively embedded into every-day objects providing ubiquitous ICT services. It is characterised by the following features (Hilty et al. 2004):

- Ubiquity: ICT becomes omnipresent in daily life but also unapparent or even invisible.
- Miniaturisation: ICT devices will shrink and become more mobile as compared to today's computers.
- Embedding: ICT is to be embedded or integrated into objects of daily use (smart things).
- Networking: Wirelessly connected ICT components exchange data with surrounding networks.
- Context sensitivity: using integrated sensors the ICT components collect and process information about their surrounding and exchange them wirelessly.

Risk: The 'effect of uncertainty on objectives' (ISO 31000) is often expressed as the possibility of loss (whereby the loss is a unintended deviation from objectives). In risk management, the possibility is calculated as the probability of occurrence, based on empirical knowledge. The loss is then understood as the severity of an expected damage. In the context of this dissertation, the term risk is applied in a meaning of uncertainty about unintended adverse side effects of emerging technologies on safeguard subjects (things that are worth to be protected from damage, e.g. the environment). Such a risk is hard to quantify ex ante, as the probability cannot be calculated due to a lack of empirical data. Moreover, there is scientific uncertainty about the nature of adverse side effects (the damage cannot be determined).

Uncertainty: Refers to incomplete knowledge about impacts. The probability and extend of impacts are not exactly known before they happen. As for established technologies, the probability and extend of impacts can be calculated based on experiences. Epistemic limits of knowledge exist in the case of emerging technologies: here, uncertainty refers to incomplete understanding of the causal factors of impacts. In cases were possible impacts are wholly unimaginable or unexpected, one speaks of ignorance. Complexity is another aspect of uncertainty of man-made technical systems (causal agent) that effects the environment. It refers to epistemological “*difficulties in identifying and quantifying causal links between a multitude of potential causal agents and specific observed effects.*” (IRGC, 2008). This results in “*our inability to predict outcomes*“ (Ehrenfeld, 2008). The notion of ambiguity refers to a state of knowledge that allows more than one interpretation of possible unintended outcomes. Ambiguity exacerbates the consequences of uncertainty in decision-making.

Technology: The notion of ‘technology’ is a dualism of products and the know-how of making artefacts. Products are the physical “*carriers*” of technology (Twiss, 1980).

Technology developers: In the context of this dissertation, this term is used as an umbrella for all actors of the smart textiles innovation system that are concerned with the solving of technical challenges. The term encompasses industrial designers and engineers as well as material scientists, applied researchers, production managers, and artists.

Samenvatting in het Nederlands

Hightech productinnovatie heeft soms negatieve bijwerkingen voor de duurzaamheid vanuit milieutechnisch perspectief. De vroege stadia van innovatie bieden een goede gelegenheid om de milieurisico's te beperken voordat zij optreden. Dit proefschrift bevat een verkenning van de anticipatiestrategieën voor ecologisch ontwerpen die een bijdrage kunnen leveren aan het beperken van de milieurisico's van slim textiel. Slim textiel is gekozen als voorbeeld van een slimme technologie in opkomst die in de nabije toekomst deel zal uitmaken van het dagelijks leven. De voornaamste onderzoeksvraag van dit proefschrift is:

"Hoe kunnen de milieurisico's van technologieën in opkomst al in een vroege fase van het ontwerpproces worden beperkt?"

Dit proefschrift bestaat uit een verzameling gepubliceerde en ingediende onderzoeksartikelen, voorafgegaan door een inleidend hoofdstuk 1, waarin het analytisch kader wordt toegelicht, evenals de onderzoeksdoelstellingen en -vragen. In de artikelen komen diverse risicoaspecten van slim textiel aan bod en worden risicobeperkingsstrategieën besproken vanuit het perspectief van duurzame innovatie en ecologisch ontwerp.

In hoofdstuk 2 komen de verwachte milieueffecten van 'pervasive computing' aan de orde. Deze technologie in opkomst wordt beschouwd als een overkoepelende innovatietrend binnen de ICT, en slim textiel maakt hier deel van uit. Twee grote milieurisico's zijn bekend: toenemend gebruik van zeldzame grondstoffen en een groeiende hoeveelheid lastig te recyclen elektronisch afval. Daarnaast zal het energieverbruik toenemen doordat er enorme aantallen zeer kleine elektronische apparaatjes op de markt komen. Slimme producten, zoals bijvoorbeeld slimme huishoudelijke artikelen, kunnen ook een bijdrage leveren aan het optimaliseren van energie- en materiaalbesparingen in andere productie- en consumptieprocessen. De omvang van de positieve en negatieve effecten is afhankelijk van het effect dat het beleid voor duurzame innovatie heeft op de ontwikkeling van ICT-infrastructuren en -producten gedurende de komende jaren.

In hoofdstuk 3 wordt uitgebreider ingegaan op de mogelijke implicaties van het einde van de levenscyclus van een specifiek soort apparatuur voor pervasive computing: elektronisch textiel. Deze nieuwe hightech producten zijn kleine elektronische apparaatjes die naadloos zijn ingebouwd in kleding en technisch textiel. Uit onderzoek naar de mogelijke gevolgen van het einde van de levenscyclus blijkt dat dergelijke producten, als het massaconsumptiegoederen worden, een nieuw, moeilijk te recyclen type afval opleveren. De omvang van de afvalstroom die het gevolg is van het gebruik van e-textiel in de toekomst is geschat op basis van scenarioberekeningen waarbij gebruik is gemaakt van eerdere ervaringen met betrekking tot de marktpenetratiesnelheid van mobiele telefoons. Als e-textiel commercieel aanslaat, zullen er naar verwachting grote hoeveelheden afval worden gegenereerd. De conclusie van het artikel is dat het innovatieproces van e-textiel kansen biedt om bepaalde effecten van het einde van de levenscyclus te voorkomen.

In hoofdstuk 4 wordt dieper ingegaan op het concept van risicopreventie tijdens de vroege fasen van technologische ontwikkeling. Als eerste komen er casestudy's over slim textiel en nanotextiel aan bod, gevolgd door een overzicht van de milieu-, gezondheids-, veiligheids- en duurzaamheidsrisico's (EHS/S) van deze technologieën. Slecht beheerste EHS/S-risico's kunnen gevaar opleveren voor bedrijven die hun bedrijfsplan baseren op technologieën in opkomst. Door de discussie omtrent EHS/S-risico's te plaatsen in de context van zakelijk risicomanagement wordt duidelijk dat bedrijven de mogelijkheid hebben om risicobeperkende innovatiestrategieën voor technologieën in opkomst te implementeren. Bedrijven kunnen zich wapenen tegen de negatieve zakelijke gevolgen van EHS/S-risico's door aandacht voor de levenscyclus en ecologisch ontwerpen te integreren in het productontwikkelingsproces.

Hoofdstuk 5 is gewijd aan de uitdagingen met betrekking tot het ecologisch ontwerpen van e-textiel. De conclusies uit de twee voorgaande hoofdstukken worden gebruikt als startpunt voor levensvatbaardere ontwerpstrategieën die een antwoord kunnen bieden op de potentiële problemen met afval als gevolg van elektronisch textiel. Tijdens ontwerpexperimenten met e-textiel is het principe 'ontwerpen voor recycling' uitgetest. Daarbij is gebleken dat de bestaande concepten voor ecologisch ontwerpen aan herziening toe zijn, omdat ze niet meer aansluiten op de eigenschappen van de convergerende technologie. In dit hoofdstuk worden mogelijke strategieën voor ecologisch ontwerpen uiteengezet met betrekking tot het einde van de levenscyclus van e-textiel. Er wordt betoogd dat ontwikkelaars van technologie standaarden voor compatibiliteit moeten ontwikkelen en hanteren om te voorkomen dat e-textiel in de toekomst steeds sneller veroudert. Daarnaast bieden slimme materialen en slimme etiketten nieuwe mogelijkheden voor hergebruik van deze hightech producten.

In hoofdstuk 6 wordt gekeken naar de bruikbaarheid van een beoordeling van de levenscyclus (Life Cycle Assessment, LCA) ter ondersteuning van de besluitvorming door milieubewuste ontwikkelaars van slim textiel. In dit hoofdstuk is een enquête onder mkb-bedrijven uit de slimme-textielbranche opgenomen. Uit de resultaten komt naar voren dat deze bedrijven in de productinnovatiefase nauwelijks gebruikmaken van LCA's. Een LCA van één slim textielproduct laat zien dat een voorafgaande LCA al voldoende is om ecologisch ontwerpen tijdens de ontwikkeling van slim textiel te stimuleren. Daarna volgt een beschrijving van een methodologisch concept in de vorm van een besluitvormingsondersteunende tool op LCA-basis voor mkb-bedrijven in de slimme-textielsector.

Hoofdstuk 7 biedt een nieuwe kijk op risicopreventie tijdens de vroege innovatiefasen. De onmisbaarheid van grondstoffen dient als voorbeeld van een immaterieel risico dat lastig is in te schatten als gevolg van de complexiteit en onzekerheid van beïnvloedende factoren. In dit hoofdstuk wordt onderzocht waarom industrieel ontwerpers en ingenieurs aandacht moeten besteden aan de onbedoelde gevolgen van technologische vooruitgang. In hoofdstuk 8 wordt dieper ingegaan op de redenen om meer bewustzijn te kweken bij industrieel ontwerpers en ingenieurs over de beperkte beschikbaarheid van onmisbare materialen. Er wordt betoogd dat de onmisbaarheid van deze materialen een nieuwe impuls kan geven aan de opleiding van industrieel ontwerpers en ingenieurs. Het is belangrijk om de professionals van de toekomst te trainen in het hanteren van een systeemgericht perspectief tijdens het proces van technologische innovatie, zodat zij ook bij een beperkte materiaalkeuze hun werk goed kunnen doen. Ter afsluiting van het hoofdstuk worden er manieren beschreven waarop dit onderwerp kan worden ingebouwd in bestaande onderwijsprogramma's.

Hoofdstuk 9 bevat een overzicht van de antwoorden op de onderzoeksvragen van dit proefschrift alsmede de bijbehorende conclusies. In dit proefschrift worden anticipatiestrategieën uitgewerkt voor de preventie van milieurisico's die samenhangen met het innovatieproces voor slim textiel. Tot deze strategieën behoren: het toepassen van ecologische ontwerpervaring op basis van een beoordeling van de levenscyclus; training en ontwikkeling van vaardigheden van industrieel ontwerpers en ingenieurs zodat zij concrete maatregelen voor ecologisch ontwerpen kunnen ontwikkelen en implementeren, en het verhogen van het risicobewustzijn van industrieel ontwerpers en ingenieurs en het aanleren van een proactieve houding ten aanzien van risicobeperking.

List of publications and conference presentations

Articles published in peer-reviewed journals

Köhler, A. and Erdmann, L. (2004). Expected Environmental Impacts of Pervasive Computing. Human and Ecological Risk Assessment 10: 831–852.
(chapter 2)

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(chapter 3)

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(chapter 8)

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Köhler, A.R. (2012): Recycling and disposal of smart textiles. 51st DORNBIRN MAN-MADE FIBERS CONGRESS, September 19-21, Dornbirn, Austria.

Köhler, A.R., et al (2012): Life cycle assessment and eco-design of a textile-based large-area sensor system. Electronics Goes Green 2012, September 9-12. Berlin, Germany.
(section 6.6)

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Köhler, A.R., Stavenga, M. (2010): How sustainable is nanotechnology really: Strategies for sustainable design of nanotechnology products. Workshop chaired at the Knowledge Collaboration & Learning for Sustainable Innovation. ERSCP-EMSU conference, October 25-29, Delft, The Netherlands.

Stamp, A., Köhler, A.R. (2010): The international PhD Network 'Scarce Elements'. Poster presented at the Gordon Research Conferences: Industrial Ecology - From Analysis to Design. July 11-16, New London, NH.

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Köhler, A.R. (2009): Sustainable innovation of emerging technologies: Exploring green design of electrically active textiles. Presentation at the PhD Workshop 'Scarce elements supply and demand: Critical issues and implications for sustainable governance'. September 13, Davos, Switzerland.

About the author

Andreas R. Köhler, was born at 9 march 1971 in Dresden, Germany. He holds a diploma degree in environmental engineering from the University of Applied Sciences Zittau, Germany (1996 - 2001) and a Master of Science degree in Environmental Management and Policy from Lund University, Sweden (2007 - 2008). Between 2001 and 2007 he worked as a research fellow at the Technology and Society Laboratory of the Swiss Federal Institute of Materials Testing and Research (EMPA). During this period he researched the implications of emerging technologies on the environmental sustainability, human health, and safety. Areas of expertise include innovation and technology assessment in the subject areas of pervasive computing, RFID, nanotechnology, e-waste (WEEE), and smart textiles. Next to his research, he worked as an auditor in the Swiss E-waste recycling system (SWICO) and as an advisor in environmental management.

In 2009 he joined the Design for Sustainability program at TU Delft (The Netherlands) as a Ph.D candidate. His research is concerned with innovation and technology assessment (ITA) & Life cycle assessment (LCA) of smart textiles. His research interest focuses at developing strategies for risk preventative technology development (reducing e-waste, and energy consumption of future products, avoiding material scarcity, by means of eco-design).

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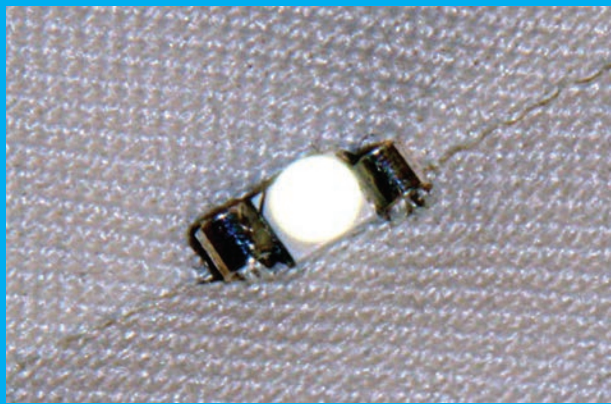
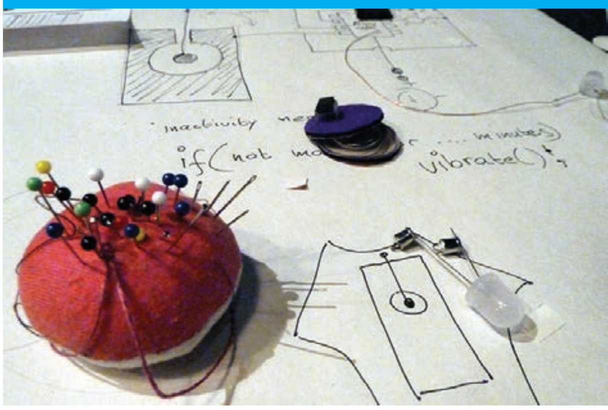
Delft University of Technology

Design for Sustainability program





This dissertation explores environmental aspects of smart textiles: products that feature a deep integration or even a fusion of textile and electronic materials. The emerging technology exemplifies a contemporary innovation trend of augmenting the functionality of every-day objects to make them smart. The environmental assessment shows that the mass application of such products can lead to increasing resource consumption (energy and raw materials) and to new waste problems at the end of the use phase.

The early stage of a technology development process holds opportunities to steer the innovation along sustainable pathways. Environmentally conscious design aims to mitigate environmental impacts of new products. The thesis presents risk preventative eco-design strategies that can help to minimise adverse environmental impacts before large amounts of smart textiles are brought to the market. Notably, the work explores how Life Cycle Assessment (LCA) can be used as a decision support tool at the early stage of product development. A simplified LCA-framework for application in the smart textiles sector is proposed.

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