THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Towards Sustainable Use of Chemicals in the Textile Industry:

How life cycle assessment can contribute

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Towards Sustainable Use of Chemicals in the Textile Industry:
How life cycle assessment can contribute

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Abstract

The use of chemicals in the textile industry is a topic that has been given increasing attention in recent years. Hazardous chemicals are found in textile consumer products on a regular basis, and there is an increased awareness of the health and environmental impact caused by emissions of hazardous chemicals in the countries where textile production occurs. There is a need for practical tools that can be used to assess and reduce the exposure of people and nature to harmful chemicals.

Life cycle assessment (LCA) is a quantitative tool that evaluates the environmental pressures and benefits associated with the full life cycle of products or services, potentially comprising a broad range of environmental impact categories, such as climate change, acidification, resource depletion and toxicity. However, accounting for the use and emission of chemicals is a weak point in LCA practice and calculating the toxicity impact is a weak point of LCA methodology, and therefore, toxicity impacts are habitually excluded from LCA studies. The drawbacks of excluding toxicity in environmental evaluations are especially critical in assessment of textile products since the textile industry is an intense user of chemicals, both for fibre production and during the textile manufacturing process.

The research presented in the thesis and the two papers intends to improve LCA methodology and practice so that use and emissions of textile chemicals can be included in LCA studies of textile products, and the results thereof can provide useful guidance to decision makers in the textile industry. Three research questions are answered: 1) if the toxicity impact potential of textile chemicals is covered in LCA studies of textile products, 2) if the environmental performance ranking of textile products will be affected by including the toxicity impact potential of textile chemicals in LCA studies and 3) what the main challenges are in using LCA to assess the toxicity impact potential of textile chemicals. The research method has been designed to explore the challenges and suggest improvements to LCA methodology based on literature studies, case studies and triangulation with other applicable methods for calculation of toxicity impact potential.

It is concluded that the toxicity impact potential of textile chemicals is today only to a marginal extent covered in LCA studies of textile products. The use and emission of textile chemicals are in general excluded from life cycle inventories. In some cases where textile chemicals have been included in the inventory they are still excluded from the toxicity assessment. It is further concluded that the total environmental performance ranking of textile products can be affected by including the toxicity impact potential of textile chemicals in LCA studies. In addition, quantification of toxicity impacts in LCA allows for the comparative significance of chemicals to be revealed. By providing such knowledge LCA allows thus for comparison of the effectiveness of different management interventions. Several challenges have been identified which must be overcome for LCA to contribute to the sustainable use of chemicals in the textile industry. The main challenges are the complexity of calculating toxicity impact potential in LCA: the complexity of the textile production chain; the diversity in both the use and properties of textile chemicals; the lack of guidance in the area in the literature and the lack of validation methods. If these challenges are addressed, LCA can contribute to a sustainable use of chemicals in the textile industry with its quantitative approach, its life cycle perspective and its holistic view of environmental impact.

Keywords: LCA, Textile, Chemicals, Impact assessment, Toxicity

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Till sist, tack till min älskade familj, Erik, Jonathan och David!

List of publications

This licentiate thesis is based on the research work presented in the following papers, which are referred to in the text by roman numerals. Manuscripts of the papers are appended at the end of the thesis.

I. Roos, S., Posner, S., Jönsson, C., Peters, G.M. (2015) Is unbleached cotton better than bleached? Exploring the limits of life cycle assessment in the textile sector. Submitted to the Clothing and Textiles Research Journal (minor revisions).
II. Roos, S., Peters, G.M. (2015) Three methods for strategic product toxicity assessment - the case of the cotton t-shirt. Submitted to the International Journal of Life Cycle Assessment.

Work related to this thesis has also been presented in the following publications.

1. Roos, S., Peters, G., (2013) "Clothes made from eucalyptus – our future? ", proceedings from LCM 2013 conference, Gothenburg
2. Roos S, Posner S, Jönbrink, A K, ”Rekommendationer för hållbar upphandling av textilier” [Recommendations for Green Public Procurement of Textiles], Swerea IVF report on commission of VGR and SLL, Stockholms Läns Landsting, 2011
3. Olsson E, Posner S, Roos S, Wilson K, ”Kartläggning av kemikalieanvändning i kläder” [Mapping chemicals use in clothes], Swerea IVF rapport 09/52 (2010) on commission of Swedish Chemicals Agency (KemI), 2010
4. Carlson R., Erixon M., Erlandsson M., Flemström K., Häggström S[1], Tivander J: ”Establishing common primary data for environmental overview of product life cycles: Users, perspectives, methods, data, and information systems”, Naturvårdsverket, 2005.

[1] Author's maiden name is Häggström

Contribution report

Paper I

The author performed the research design, did all the life cycle assessment modelling, and performed the supplementary chemicals assessment together with Mr. Stefan Posner. The author also wrote the article with feedback from all co-authors.

Paper II

The author performed the research design, did all the modelling and wrote the article with feedback from the co-author.

List of abbreviations

CF	Characterisation Factor
CLP	Classification, Labelling and Packaging of substances and mixtures (European Regulation (EC) No 1272/2008)
CTUe	Comparative Toxic Unit for ecotoxicity
CTUh	Comparative Toxic Unit for human toxicity
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory analysis
LCIA	Life Cycle Impact Assessment
NGOs	Non-Governmental Organisations
NMVOC	Non-Methane Volatile Organic Compounds
PEF	Product Environmental Footprint
RAPEX	European Rapid Alert System for non-food dangerous products
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RSL	Restricted Substance List
SAICM	Strategic Approach to International Chemicals Management
SDS	Safety Data Sheet (also termed Material Safety Data Sheet, MSDS)
SVHC	Substances of Very High Concern

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1 Introduction

In recent years increased attention has been given to the chemicals which are contained in textile products (Munn, 2011), as well as exposure of textile industry workers to hazardous chemicals and environmental effects in the countries of production (Stenborg, 2013). There is a need for more knowledge and also practical tools that can be used to reduce the exposure of people and nature to harmful chemicals. The use of quantitative measurement tools such as life cycle assessment (LCA) (ISO, 2006a) for evaluation of chemicals is today not widespread in the textile industry. Indeed there are challenges in applying LCA on textile chemicals which will be presented in this thesis. At the same time there is also a large potential for LCA to become a useful complement to both legislation and other initiatives for sustainable management of chemicals in the textile industry if the methodology can be further developed. The concept of sustainable use of chemicals, the research context and the life cycle assessment methodology will be presented to the reader in the following introduction sections.

1.1 Sustainable use of chemicals

Sustainability has been generally defined in the Brundtland Commission Report:

> "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs"
> (Word Commission on Environment and Development, 1987)

Sustainable development from a holistic perspective comprises economic development, social development and environmental protection (UN General Assembly, 2005). The specific aspect of adverse impacts from chemicals is one of the environmental aspects relevant for sustainable development alongside with greenhouse gas emissions, water depletion, resource depletion, acidification, and so forth. In 2002, at the Johannesburg World Summit on Sustainable Development, the participating countries agreed to the following goal concerning chemicals:

> “by the year 2020, chemicals are produced and used in ways that minimize significant adverse impacts on the environment and human health”
> (United Nations, 2002, paragraph 23)

This statement defines sustainable use of chemicals for the purpose of this thesis.

The term chemical can have different interpretations. For the purpose of this thesis, the term “chemical” is used both for a specific substance, in general identifiable by a Chemical Abstract Service Registry Number (CAS RN) (American Chemical Society, 2014), and for a mixture of such chemical substances. The term “textile chemicals” is used for chemicals that are directly involved in any part of the textile life cycle. Emissions of chemicals from energy production and fuel use, such as carbon dioxide and particulates, are, for the purpose of this thesis, not considered to be textile chemicals.

1.2 Research context

1.2.1 The Mistra Future Fashion programme

The research presented in this thesis has been conducted within the Mistra Future Fashion programme, www.mistrafuturefashion.com. The programme aims to develop insights and solutions, which in their turn can improve the sustainability of the Swedish fashion industry. One of the objectives is to improve sustainability assessment methodologies for ecolabelling and decision support tools. As the main recipient of this programme is the Swedish fashion industry, the focus of the thesis is primarily Swedish and European conditions.

1.2.2 Current legislation and voluntary actions on sustainable use of chemicals

As a result of the Johannesburg World Summit, four years later the Strategic Approach to International Chemicals Management (SAICM) was adopted at the International Conference on Chemicals Management (ICCM) in 2006 in Dubai, as a policy framework to foster the sound management of chemicals (United Nations Environment Programme, 2006). The European chemicals legislation REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) (European Commission, 2006) entered into force the next year, harmonising the chemicals legislation in the European Union and the European Economic Area (EEA) countries (Norway, Iceland and Lichtenstein) and regulating chemicals in many product groups that were not regulated before. REACH has also inspired several countries to develop similar regulations, often called “China REACH” (China Ministry of Environmental Protection (MEP), 2010), “K-REACH” (South Korean Ministry of the Environment, 2011) or “India REACH” (Government of India, 2012) in common terms.

From the Swedish and European perspective it is important to bear in mind that any national (or federal) regulation of chemicals is restricted to actions inside their area of jurisdiction. This circumstance means that for example the European legislation can only regulate the chemical content of products produced in, imported to or used in the European Union. The textile supply chain is on the contrary global and it is the rule rather than the exception that textile products and semi-finished products are exported and imported between these areas of jurisdiction. There are many similarities but also dissimilarities in the regulation of chemicals in different legislation frameworks such as Proposition 65 (California Environmental Protection Agency’s Office of Environmental Health Hazard Assessment (OEHHA), 1986), the Canadian Environmental Protection Act (Government of Canada - Department of Justice, 2000) and the EU harmonised chemicals legislation that includes REACH and other related product legislation. The legislative differences are not limited to the formulation of the chemicals regulations but include also the procedures of enforcement such as inspections and sanctions. Also, within the European Union there are still examples on national legislation on chemicals, which is allowed as long as the national legislation is not in conflict with EU harmonised legislation.

Textile products are further defined as “articles” under REACH in contrast to products defined as “substances and preparations” that can be exemplified with paint and detergents (European Commission, 2006). This creates a difference in the legal obligations for a supplier to provide information on the chemical content in the product. For articles, the only legal requirement that REACH imposes is the requirement to communicate in the supply chain about any Substances of Very High Concern (SVHC) contained in the product. The SVHC substances are currently a group of 161 substances that have been identified as the most potent threats to health and environment due to inherent hazardous properties, large yearly volumes and/or dispersive use patterns. Besides the actors’ legal obligation of informing about SVHC substances very little information is today communicated in the textile industry around the real constituents of the textile materials. The communication that is made on voluntary basis is generally limited to lists of unwanted chemicals, e.g. in the forms of Restricted Substance Lists (RSLs). The textile industry has thus based its communication about product content on what is the product *does not contain* instead of declaring what the product *does contain*. This is a special feature of the textile industry compared to e.g. the paint industry where chemical content is required by law to be communicated through Safety Data Sheets (SDS) (Fransson, 2012).

Legislation can thus be identified as one measure to achieve the objectives of the SAICM initiative, where industry voluntary action is another. The absence of a legislative framework that covers the entire textile supply chain has forced the industry to secure a responsible chemicals management framework based on voluntary actions which is described in section 1.2.4 of this thesis. The challenges of chemicals management in the industry, whether imposed by legal or voluntary actions, are partly due to the use and occurrence of a vast number of chemical substances, and partly in the diversity of the health and environmental impacts that result from exposure to the chemicals of humans and nature.

1.2.3 The issue with chemicals in the life cycle of textile products

The apparel and textile industry is among of the world's largest, with a total share of 4 % in world merchandise trade. The global exports of textiles and clothing were 708 billion US dollars in 2012 (WTO, 2013). The total product mass of the global textile industry amounted to 85.9 million tons in 2011 (Oerlikon, 2012). The textile industry is also an intense user of chemicals, both for fibre production and during the manufacturing process (Munn, 2011). To produce 1 kg of garment today, it has been estimated that between 1.5 and 6.9 kg of chemicals is needed, which means that the weight of the chemicals used in the production process is larger than the weight of the finished garment itself (Olsson et al., 2009). The emissions of toxic chemicals from textile production have been subject to considerable global media attention in recent years such as the Greenpeace Detox Campaign (Brigden et al., 2012). In a recent Swedish media coverage study of the chemical risks of textiles by Stenborg (2013), the chemicals in focus of the product alarms were found to be nonylphenol ethoxylates, dimethyl fumarate and phthalates. Nonylphenol ethoxylates are a group of surfactants used upstream in the textile supply chain that are classified as SVHC because of their breakdown products nonylphenols that are both endocrine disrupters and environmental toxicants. Dimethyl fumarate is a fungicide used to protect goods from mould that is restricted due to its potent allergenic properties. Phthalates are used as plasticizers in polymeric materials and several phthalates are classified as SVHC because of reproduction toxic properties. The today legally restricted phthalates are also a common reason for products to be reported in the European Rapid Alert System for non-food dangerous products RAPEX (European Commission, 2013a).

Textile products are worn, many times in direct skin contact, by everybody throughout the world, from newborn babies to sick and sensitive persons. The current existing regulation does not cover all hazardous chemicals that may occur in textiles, e.g. allergens and endocrine disrupters, and chemicals that are themselves legal may have hazardous breakdown products. As has been described above, the implementation of legislation differs significantly between countries and among product groups. Regulation of a chemical is not *per se* a guarantee that it will not occur in a product, and content of restriced chemicals is regularly reported in RAPEX (European Commission, 2014a).

The chemicals of concern for textiles are located along the whole life cycle of the textile product. Figure 1 shows a schematic picture of the different processes that represents the textile life cycle and defines the nomenclature of textile processes that will be used throughout this thesis.

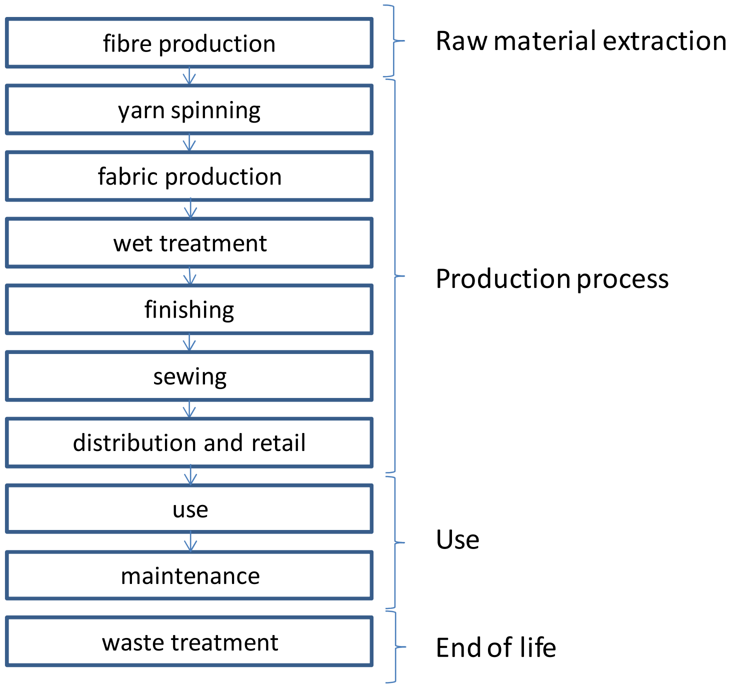

Figure 1. Schematic picture of the life cycle of a textile product, from the raw material extraction to the end of life.

Chemical pollution is one of two areas within the planetary boundaries concept developed by Rockström et al. (2009) for which it has not yet been possible to determine a boundary level, which reflects the complexity of assessing the environmental and health impact of chemicals. Table 1 attempts to summarize the adverse effects associated with textile chemicals in each of the life cycle phases for a textile product.

Table 1. Overview of the adverse effects associated with chemicals in the textile life cycle, sorted after the life cycle phase in which they occur.

Life cycle phase	Chemicals	Adverse effects
Fibre production	Pesticides Fertilisers Crude oil Surfactants Monomers Catalysts	Ecotoxicity Eutrophication Human toxicity
Yarn production (spinning)	Spinning oils	Ecotoxicity Eutrophication
Fabric production (knitting/weaving/non woven process)	Lubricants Sizing agents Needle oils	Ecotoxicity Eutrophication
Wet treatment (scouring/bleaching/dyeing)	Detergents Lubricants Stabilizers Bleach Dyestuff Salts Softeners Finishing agents Water emissions COD	Acidification Ecotoxicity Eutrophication Human toxicity Salinisation
Finishing (drying/wet coating/dry coating/printing)	Air emissions Prints Finishing agents	Ecotoxicity Human toxicity
Sewing	Stain removal Spray bleaching	Ecotoxicity Human toxicity
Distribution and retail	Biocides Container gas Fuel combustion	Acidification
Use	Skin contact Fading	Ecotoxicity Human toxicity
Maintenance (laundering, mending)	Linting of microfibres Detergents Softeners	Ecotoxicity Eutrophication Human toxicity
Waste treatment	Pollutants in recycled materials Air emissions Water emissions	Ecotoxicity Human toxicity

The implications of the use of chemicals in one phase of the life cycle may be limited to local exposure on the environment, or carry over adverse effects also to the following phases of the life cycle. An example of the latter is the choice among dyestuffs for textiles. This choice is crucial for the local environment at wet treatment sites in the exporting countries, as dyestuffs can be carcinogenic, toxic and/or persistent (Shams-Nateri et al., 2014). The choice of dyestuff is by the same rationales relevant for the environment in the importing countries but also for consumer health in order to avoid carcinogenic and allergenic properties (Malinauskiene, 2012; Sasaki et al., 2008). Textile consumer products and waste water from laundering have been found to contain undesirable degradation products such as carcinogenic arylamines from azo dyes, as well as residues of process chemicals used in the dyeing process such as alkylphenol ethoxylates.

One of the points made in the previous section, that legislation is restricted to actions inside the area of jurisdiction, must here be emphasized again since classification of a chemical as hazardous (carcinogenic, reproduction toxic, persistent and so forth) is a political decision for legislation. The obligations that follow a decision to classify a chemical as hazardous within e.g. the European Union such as the obligation to provide an SDS or inform about the content of SVHC, are not global.

The textile industry is global and one of the longest and most complicated industrial chains in manufacturing industry (Munn, 2011). It is a fragmented and heterogeneous sector dominated by small and medium sized enterprises (SME) (European Commission, 2003). Chemicals management is therefore difficult in the European textile industry that mostly represents companies that trade textile goods from Central Asia and the Far East (Munn, 2011). A few decades back, the production of textile chemicals and textiles for the European market was mainly located in Europe. The information exchange between the chemicals experts and the textile processing experts was performed directly on site. Today the chemicals content of product is controlled by actors in remote parts of the supply chain whom the textile brands have little contact with. In addition there are linguistic barriers and cultural differences that hinder and confuse the exchange of knowledge.

1.2.4 Sustainable use of chemicals from a textile product's perspective

The communication about the use of chemicals in the textile industry is today mainly based on lists of unwanted chemicals in the final product, e.g. in the forms of Restricted Substance Lists (RSL) (Fransson, 2012). The reliability of an assertion from a supplier that the customer's RSL has been followed will depend on the supplier's knowledge level and driving forces. When the supplier limits its communication concerning chemicals to an assertion that the chemical content is compliant with current regulations, this does further not encourage substitution of questionable chemicals to solutions with fever health and environmental impacts.

The main disadvantage of limiting the scope of communication to product chemical content, is that the significant environmental effects may not be linked to product content. In fact, unwanted chemicals can still be used as long as they are removed (e.g. washed out) from the product before shipment to the customer. Figure 2 below illustrates that the exposure routes from textile chemicals are not limited to emissions from the product.

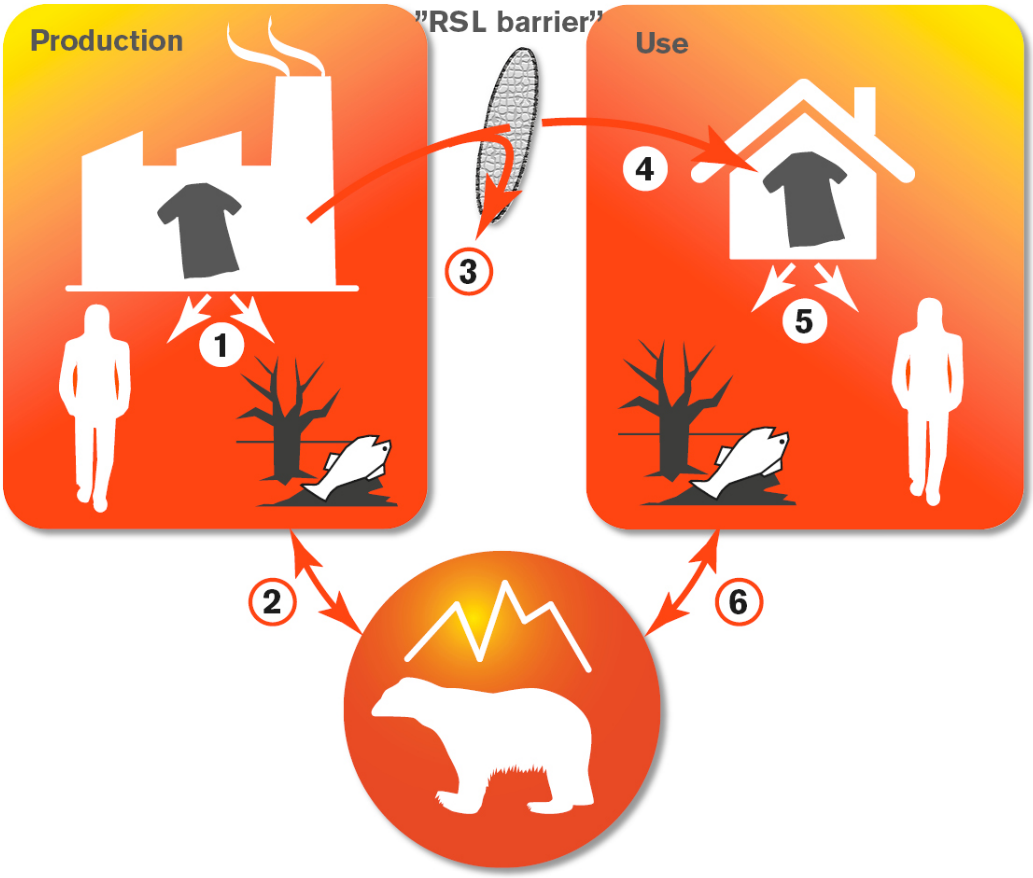

Figure 2. The scope of RSL (the "RSL barrier") is limited to product content and does not necessarily encourage substitution of hazardous chemicals with less hazardous alternatives from a life cycle perspective. The production process may lead to exposure of humans and the environment to hazardous chemicals (1) locally at the production site and (2) in remote environments by long range transport of persistent chemicals. The RSL barrier will hinder chemicals that are restricted by current legal and policy frameworks from being present in the product (3) but let through chemicals that are not (yet) restricted (4). The content of hazardous substances in the textile product can lead to exposure of humans and the environment to hazardous chemicals (5) locally at the consumption site and (6) in local and remote environments by long range transport of persistent chemicals.

In addition, a business to business (B2B) legal compliance assertion does not help consumers to select safer products. The textile industry has developed a number of different voluntary initiatives such as third party certifications, organisations auditing at the production sites and information management tools. The dominating environmental label in the textile industry is today OEKO-TEX® 100 (OEKO-TEX® Association, 2013) which guarantees the absence of hazardous chemicals in the textile product, based on laboratory testing. Other textile companies choose to follow schemes such as Bluesign® (BLUESIGN®, 2013) or the Chemicals Management Framework (Outdoor Industry Association, 2014) to manage chemical impacts in the supply chain. Textile companies commonly also engage with the Business Social Compliance Initiative (BSCI, 2013) or the Fair Wear Foundation (FWF, 2014) for managing social sustainability. Another example on a voluntary initiative is the Swedish Textile Water Initiative (STWI, 2014) that aims to improve water management in the textile supply chain.

1.2.5 The growing importance of life cycle assessment in decision making

The most popular environmental management practices in the textile industry today are generally based on single issue approaches (Charter and Clark, 2008). Some have been presented in the section above. The textile industry is however faced with a multitude of environmental challenges, essentially climate change, depletion of water and fossil resources beside the issues with chemicals (Allwood et al., 2006), while land use is increasingly attracting attention (Sandin et al., 2013). Life Cycle Assessment (LCA), Cradle to Cradle® (C2C®) (McDonough & Braungart, 2002) and the Higg Index from the Sustainable Apparel Coalition (SAC) (2012) are examples of tools for holistic management of sustainability in the textile industry. The holistic perspective reduces the risk that a decision aimed at reducing pollution simply shifts the environmental problem from one life cycle phase to another or from one environmental issue to another as is shown in Paper I.

In the EU Integrated Product Policy work, LCA was identified as the "best framework for assessing the potential environmental impacts of products currently available"(COM, 2003). The European "Ecodesign Directive"(European Commission, 2009) as well as the European Commission initiative for Product Environmental Footprint (PEF) (European Commission, 2013) is based on LCA and is currently in the pilot phase where textiles are one of the pilot cases. The SAC (SAC, 2012) also encourages LCA-based environmental product declarations (EPD) of textile products and is in the process of developing guidance material for how to create Product Category Rules (PCR). In a comparison made by Bor et al. (2011) LCA differs from C2C® in that it is a quantitative and holistic methodology and is independent of commercial interests. The Higg Index and the complementary Chemicals Management Framework from the Chemicals Management Working Group (Outdoor Industry Association, 2014) are primarily based on the evaluation of management interventions (management measures) and thus do not possess the quantitative character of environmental assessment that LCA holds.

As the use of LCA for policy making in both industry and the public sector is continuously increasing (European Commission, 2014b; Peters, 2009) it is important that LCA is developed further to enhance its relevance and reliability as a methodology for the textile industry. Accounting for the use and emission of chemicals is a weak point in LCA methodology and toxicity impacts are habitually excluded from LCA studies. The drawback of not including toxicity in environmental evaluations is especially critical in assessment of textile products since the textile industry is an intense user of chemicals.

1.2.6 Risks with non comprehensive inclusion of chemicals issues in LCA of textile products

The importance of including chemicals in LCA has been reported in several studies (Hitchcock et al., 2012; Larsen et al., 2009; Laurent et al., 2012; Panko and Hitchcock, 2011). With the European Commission initiative for PEF (European Commission, 2013b) now being applied for textile products, the toxicity of chemicals will by default be addressed in LCA of textiles, which makes it important that the results are not misleading and that the intended users feel confident to take action based on the results.

However, one of the lessons learnt from the development of the International Reference Life Cycle Data System (ILCD) was that the number of chemicals characterised by ecotoxicity and human toxicity models is a relatively small percentage of the chemicals in use (Sala et al., 2012). It is not uncommon in LCA studies to neglect the production and use of chemicals (Sala and Goralczyk, 2013) and when chemicals are included, the toxicity scores from three commonly used LCA methods were recently shown to generate inconsistent results (Owsianiak et al., 2014). The calculation of toxicity impact is thus challenging, and not only for textile products. In a recent article on LCA on textiles, Terinte et al. (2014) excluded toxicity impacts and stated that the inventory data was incomplete for textile chemicals and that there was also a lack of recommended characterisation factors for specific compounds. Another option popular in research projects is to perform an Environmental Risk Assessment (ERA) as a complement to LCA (e.g. Herva et al., 2011; Liu et al., 2012) though the ERA and LCA have different aim and scope (Flemström et al., 2004). To a large extent however the ERA will be based on the same primary data as is needed for the toxicity assessment in the LCA, giving this combination a larger potential for synergy than is usually exploited (Carlson et al., 2005).

The disregard of chemical issues in sustainability assessments can lead to erroneous conclusions and guide sustainable development in the wrong direction. One example is the recent ranking of conventional cotton as a material of low environmental impact based on only global warming potential (Muthu et al., 2012), not considering the serious impacts of ecotoxicity from the cotton cultivation (BCI, 2013). An example of non comprehensive inclusion of chemicals issues that risk to deliver erroneous conclusions in the assessment of textile products is the Made-By index of textile fibres (MADE-BY, 2013). This index bases the chemical score on the most significant hazard phrase of any of the chemicals included in the production of a fibre, disregarding volumes, all other chemicals and whether there is a risk of exposure to the most hazardous chemical or not.

While strictly speaking there can be no experimental validation of environmental damage predicted in an LCA of a garment, benchmarking of the results of different methods can be considered a form of triangulation in LCA (Peters et al., 2013) which can potentially provide confidence in the individual methods (Bryman and Bell, 2011), as is proposed in Paper II. The work load on the LCA practitioner applying each toxicity assessment method will also be discussed as this is an important parameter influencing whether the method will be viable and also correctly employed.

1.3 Life cycle assessment methodology

Life cycle assessment (LCA) is a quantitative tool that evaluates the environmental pressures and benefits associated with the full life cycle of products or services, from raw material extraction through materials processing, manufacture, distribution, use, to disposal or recycling, see Figure 1 in section 1.2.3. Environmental impacts include emissions to air, water and soil as well as the use of resources in the form of energy, water, material and land area, in the different stages of the life cycle.

According to the ISO 14040 and 14044 standards (ISO, 2006a, 2006b), an LCA is carried out in four distinct phases: 1) goal and scope definition; 2) life cycle inventory analysis (LCI); 3) life cycle impact assessment (LCIA) and 4) interpretation of results. The iterative character of LCA, to allow for adjustments as a result of new insights, is described by the arrows back and forth between the phases in Figure 3 below.

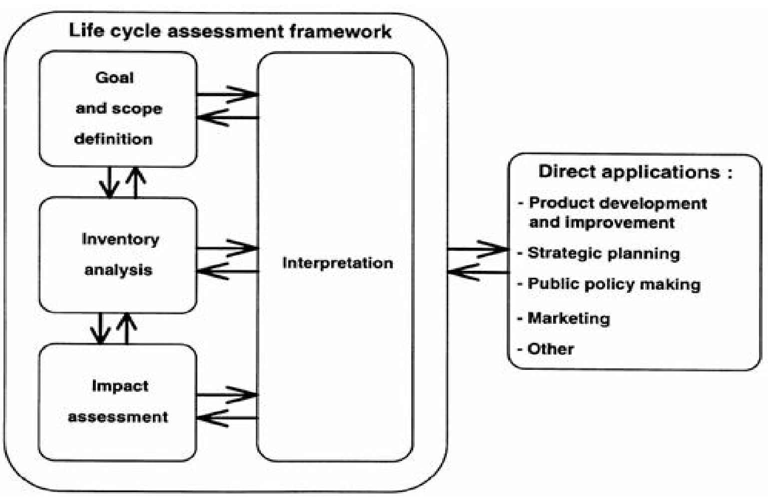

Figure 3. The four phases of an LCA and their interrelations in the LCA framework, from the International Standard ISO 14040.

The goal and scope definition includes defining the *functional unit* which is an important concept in LCA. The functional unit is a quantitative measure for the product's function, e.g. one day of use for a garment, which enables comparisons of different products with identical function. The following description of LCA as a method will be focused on the match between LCI and LCIA. For more description of LCA methodology in general the reader is referred to ISO 14040, ISO 14044 and the handbook produced by the European Commission (2010).

The LCI result is a comprehensive list of relevant inflows and outflows, an inventory of energy and materials for each process included in the product's life cycle. The LCIA method used in the impact assessment contains characterisation factors (CF) that relate the inflows and outflows quantitatively from the inventory to potential environmental impacts (Pennington et al., 2004). The CF is a linear factor which for chemicals is typically calculated using a steady-state, multimedia and multicompartment model of the environment. To be included in the LCA, an emission of chemicals must thus be both listed in the LCI and have a CF, as Figure 4 illustrates.

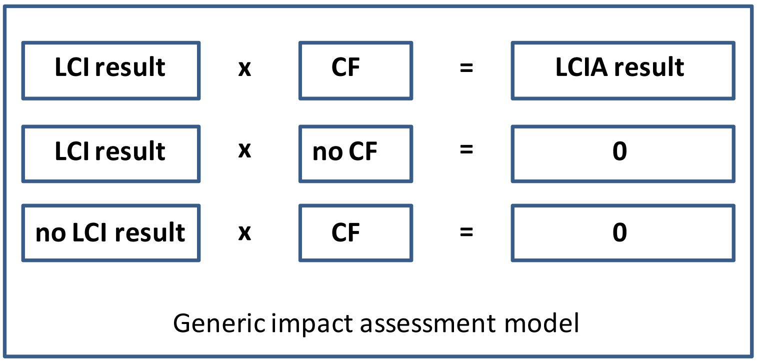

Figure 4. The emission of a chemical must both be listed in the LCI and have a CF to be included in the LCA.

The message may seem obvious but as will be seen in the results in Chapter 3.1, this fact is often neglected. The last phase is the interpretation of the results where uncertainties in the results and e.g. the limitations in the coverage of the CF are very important to disclose according to the guidelines of ISO 14044 (ISO, 2006b).

Figure 5 illustrates an example where an emission of 1 kg formaldehyde to urban air is listed in the LCI and converted by a generic impact assessment model, in this case USEtox, to three potential impact categories: human toxicity potential, ecotoxicity potential and photochemical ozone creation potential. The results are expressed in the common unit of the category indicator: 25.4 µCTUh (Comparative Toxic Unit for human toxicity), 27.6 CTUe (Comparative Toxic Unit for ecotoxicity) and 0.877 kg NMVOC (Non-Methane Volatile Organic Compounds) equivalents.

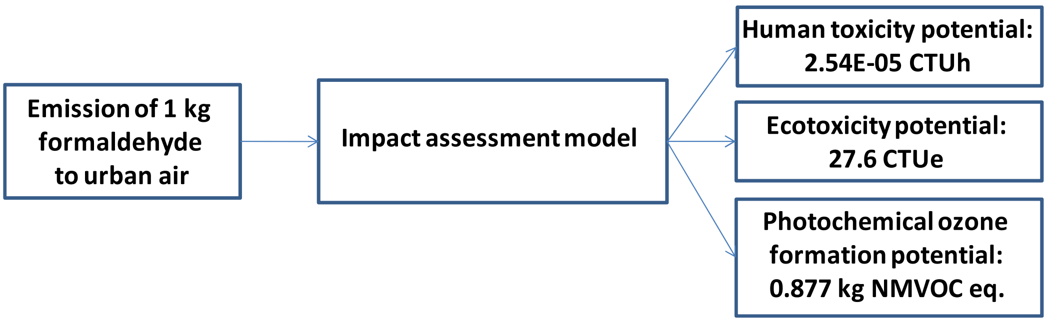

Figure 5. The mechanism of the generic impact assessment model is to convert the LCI result to the common unit of the category indicator. In this example the LCI result is an emission of 1 kg of formaldehyde to urban air. The category indicators are CTUh, CTUe and kg NMVOC equivalents respectively.

1.3.1 Methodological frontier of LCIA methods for chemicals

The expression "footprint" has in general come to mean a quantitative indicator showing the appropriation of natural resources by human being (Hoekstra, 2008) where LCA is one of the most used methodologies for calculating the footprint using a certain LCIA method for each footprint or impact category. The European Platform on LCA is a project of the European Commission that makes recommendations to the LCIA method to be used for each of the different impact categories in their ILCD handbook (European Commission, 2011). The list of impact categories related to adverse effects of chemicals is long in the overview of footprint analysis tools by Čuček et al. (2012), where chemical footprint, emission footprint, nitrogen footprint and phosphorous footprint covers both toxic and non-toxic effects of chemicals. To this list is also recently added the odour footprint (Peters et al., 2014). The different types of environmental impact that can be attributed to textile chemicals were briefly described as acidification, ecotoxicity, eutrophication, human toxicity and salinisation in the overview of the adverse effects associated with chemicals in the textile life cycle in Table 1.

The research presented in this thesis will focus on toxicity impacts from textile chemicals, partly because there is a consensus model to be applied and partly because toxicity is perceived as the most urgent aspect of chemicals by both researchers (Larsen et al., 2009) and media (Stenborg, 2013). In their editorial from 2011, Hauschild et al. (2011) foresaw a bright future for addressing 'chemical emissions' in LCA, pointing to that the method development for LCIA of the *toxicity* impact potential of chemicals has taken several important steps forward in recent years. As the development of CFs is resource demanding, previous studies have used a range of methodologies for simplified incorporation of toxicity in LCIA. A common approach has been to merge the life cycle perspective with chemical risk information to deal with the problem of missing CF for toxicity impacts (Askham, 2011; Finnveden et al., 2009; Laurent et al., 2012; Liu et al., 2012; Scheringer, 1999). With the development of the consensus model USEtox (Rosenbaum et al., 2008) the LCA community has converged in the assessment of toxicity and USEtox is recommended both by the ILCD handbook (European Commission, 2011) and the Product Environmental Footprint (PEF) work (European Commission, 2013b). The next chapter gives an introduction to USEtox.

1.3.2 The USEtox consensus model

There are many different impact assessment models available to the LCA practitioner. ReCiPe (Goedkoop et al., 2008), Eco-indicator 99 (Goedkoop and Spriensma, 2000) and CML 2001 (Guinée et al., 2002) are commonly used in LCA studies. The USEtox consensus model (Rosenbaum et al., 2008) was selected for the research presented in this thesis because it is the method recommended by the ILCD handbook and chosen for the PEF. USEtox is a global, nested box model of the transport and fate of contaminants which was developed for assessment of human toxicity and freshwater ecotoxicity within LCA. It is the consensus model resulting from extensive comparison of existing LCA methods for toxicity impact assessment by an international team of LCA experts (Rosenbaum et al., 2011) and has been used by both academic and industry LCA experts in a number of published studies. Figure 6 gives an overview of the USEtox model.

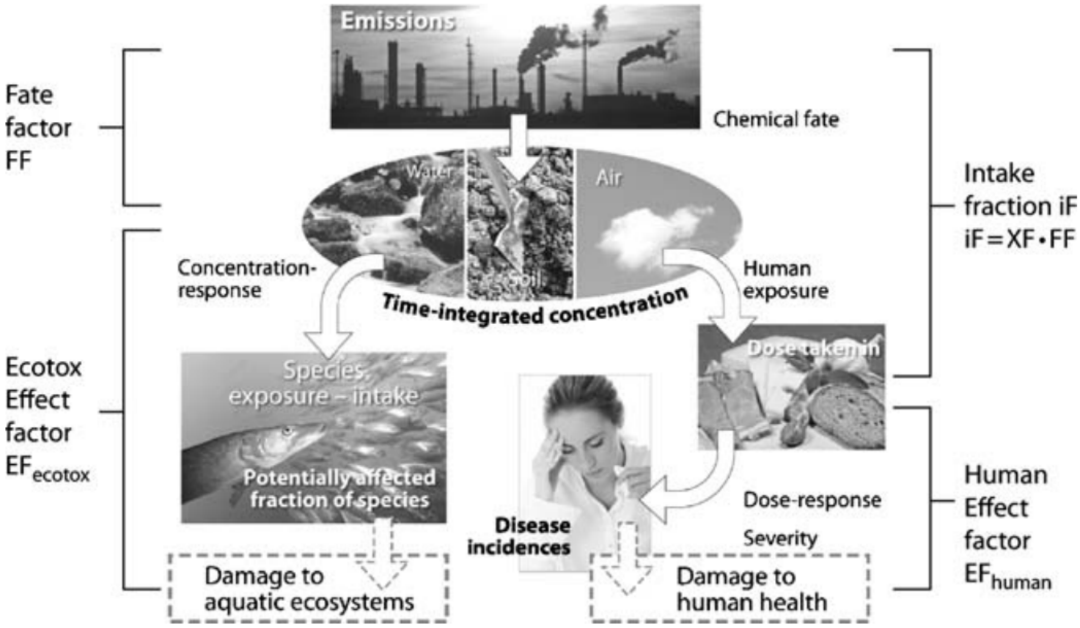

Figure 6. Overview of the USEtox method, from (Rosenbaum et al., 2008).

The Fate factor (FF) describes the environmental fate of the chemical ("what does the environment do with the chemical"). The multimedia model in USEtox consists of the compartments air, water, soil and sediment, each divided into local, continental and global scale, see figure 7.

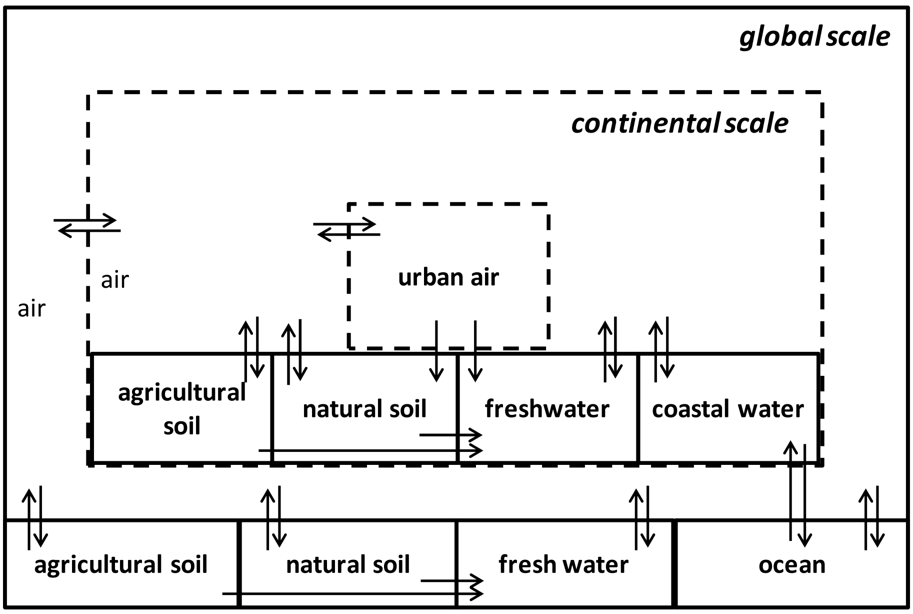

Figure 7. Compartment setup of the consensus model, from (Rosenbaum et al., 2008).

A chemical that is emitted will spread between the compartments depending on its physico-chemical properties. The USEtox fate model calculates steady-state concentrations in the compartments based on initial dilution at the local scale, transfer and dilution at a continental scale, and further transfer and dilution at the global scale. The persistence of chemicals is handled in these nested boxes in USEtox in terms of that the lower degradation rates of the persistent chemicals lead to higher steady-state concentrations in the model compared to degradable chemicals. Subsequently, the exposure and effects are larger for persistent chemicals since they are related to the steady state concentrations in the environment. This treatment of persistence in USEtox is further discussed in Paper II.

The Effect factor (EF) describes the impact of the chemical on the environment ("what does the chemical do with the environment"). For this the average of available EC_{50} values[2] are used (i.e. HC_{50}[3]) is used for ecotoxicity and the equivalent for human toxicity is the ED_{50} values[4]. For human toxicity, intake fractions (iF) are further used to model how much of a chemical emitted to the environment that will be taken in by the human population via food and water consumption, and inhalation. An important limitation of the method is the current exclusion of indoor air emissions and effects from skin contact with chemicals, issues that are under development within the LCA community. For more information on the USEtox model is referred to Rosenbaum et al. (2008).

1.4 Guide for readers

Chapter 2 describes the overall aim of the research, defines the specific research questions that this thesis intends to answer, and describes the methodological approach.

Chapter 3 discusses the research findings in the publications that this licentiate thesis is based on and how the research contributes to answering the research questions in Chapter 2.

Chapter 4 presents the conclusions from the research.

Chapter 5 gives recommendations for future research.

[2] EC_{50} is the Effect Concentration at which 50% of the exposed population exhibit a response after a specified exposure duration.
[3] HC_{50} (in USEtox also called avlogEC50) is the Hazardous Concentration at which 50% of the species are exposed above their EC50.
[4] ED_{50} is a pharmaceutical term for the Effective Dose required to achieve 50% of the desired response in 50% of the population.

2 Aims and Approach

2.1 Overall aim of research

The overall aim of the research is to provide knowledge and tools that can be used to reduce the exposure of people and nature to harmful chemicals. The research presented in the thesis and the two papers intends to improve LCA methodology and practice so that use and emissions of textile chemicals can be included in LCA studies of textile products, and the results thereof provide useful guidance to decision makers in the textile industry. The research focuses on three research questions.

2.2 Research questions

Research question 1. Is the toxicity impact potential of textile chemicals covered in LCA studies of textile products?

The first research question is formulated in a practical context in which LCA has become an important tool in society for assessing the environmental impact potential of textile products, as section 1.2.5 describes. Decision makers expect holistic assessments. Including toxicity in an environmental assessment is especially crucial for textile products since the adverse effects of chemicals constitute an important environmental challenge, as is described in section 1.2.3. Paper I presents a literature study of the current practice regarding how toxicity of textile chemicals is handled in LCA studies. Updated and more detailed information is presented in Table 3 of this thesis.

Research question 2. Will the environmental performance ranking of textile products be affected by including the toxicity impact potential of textile chemicals in LCA studies?

Section 1.2.6 describes how toxicity impacts are generally omitted from LCA studies. Would the overall results from LCA studies of textile products differ if the toxicity impact potential of textile chemicals was included?

Paper I investigates the methodological frontiers of LCA for calculation of toxicity impact potential of textile chemicals. The life cycle perspective and quantitative approach of LCA is compared with some of the predominant qualitative chemicals management interventions in the textile industry today. The case study of hospital garments in Paper I was set up to investigate whether LCA can give a comprehension of the comparative significance of the textile chemicals used during the textile product's life cycle. Will the recommendations for chemicals management differ if the toxicity potential associated with different textile chemicals is related to the end product's function, the functional unit, as entailed by the LCA approach? Will the life cycle perspective and quantitative approach of LCA avoid the undesirable phenomenon of suboptimisation, i.e. improving just a part of a system in a manner that negatively affects other parts of the system?

Research question 3. What are the main challenges in using LCA to assess the toxicity impact potential of textile chemicals?

Paper II explores the current challenges in making LCA a useful tool to contribute to a sustainable use of chemicals in the textile industry, in terms of both method and practice. Can the results be validated so that the end-user, the decision maker, can be confident to take actions based on the results? Are the challenges with toxicity assessment in LCA with respect to textile chemicals too complex for LCA practitioners to apply the method correctly in practice? What are the benefits and drawbacks of possible simplifications that can be made?

2.3 Overall methodological approach

LCA as defined by the ISO 14040 standard (ISO, 2006a) is the environmental assessment tool applied and evaluated in this thesis. The research method has been designed to explore the challenges and suggest improvements to LCA methodology based on literature studies, case studies and triangulation with other applicable methods for calculation of toxicity impact potentials of textile chemicals.

2.4 Research method

The first research question is most appropriately answered by a literature review (Bryman and Bell, 2011) of both academic and non academic publications. In the first part of the research, a comprehensive literature study was performed. The standard databases for academic literature: Scopus, SciFinder and ProQuest were used. The search phrases are listed in Table 2 below. No limitation regarding temporal coverage was applied.

Table 2. Search phrases for the literature search in Scopus and ProQuest.

Search phrase	Number of hits
(TITLE-ABS-KEY[5](textile* AND chemical*) AND SRCTITLE[6](life cycle assessment))	6
(KEY[7](chemical*) AND SRCTITLE(life cycle assessment))	89
(TITLE-ABS-KEY(chemical* AND toxicity) AND SRCTITLE(life cycle assessment))	48
(TITLE-ABS-KEY(chemical* AND toxicity) AND SRCTITLE(journal of cleaner production))	25
(TITLE-ABS-KEY(chemical* AND life cycle assessment) AND SRCTITLE(environmental science AND technology))	373
(TITLE-ABS-KEY(chemical* OR pollut* OR toxic* OR solvent* OR plastici*er OR pesticide* OR softener* OR dye* OR colourant* OR colorant* OR degradation)) AND (TITLE-ABS-KEY(textile* OR garment* OR apparel* OR cloth* OR fabric OR yarn OR fibre* OR fiber* OR cotton OR polyester OR polyamide OR viscose)) AND (TITLE-ABS-KEY(life cycle assessment))	248
(TITLE-ABS-KEY(toxicity AND life cycle assessment) AND SRCTITLE(environmental science AND technology))	49
(TITLE-ABS-KEY(textile* AND life cycle) AND SRCTITLE(environmental science AND technology))	3
(TITLE-ABS-KEY (textile* AND life cycle) AND SRCTITLE (journal of cleaner production))	9
(TITLE-ABS-KEY(textile*) AND SRCTITLE(Sustainability))	32

For SciFinder, the search phrase “life cycle assessment of textile” was used. Google was used as the search tool for non academic literature. Reference and citation search was also performed for the publications that were relevant. To enhance the comprehensiveness, the results were sorted on the basis of the textile life cycle phase (see Figure 1) and the fibre material, in order to make potential gaps visible, the results are found in Table 3.

The second research question was explored in a case study commissioned by the Stockholm County (SC). Here, cradle-to-gate (ISO, 2006b) attributional (European Commission, 2010) LCA that included textile chemicals was performed on hospital garments. According to Yin (2009), a case study is an empirical inquiry that investigates a contemporary phenomenon in depth and within its real-life context,

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[5] The search phrase TITLE-ABS-KEY commands search in title, abstract and keywords.
[6] The search phrase SRCTITLE commands search in the source title (the journal’s title).
[7] The search phrase KEY commands search in keywords. Since “chemical” can be included in e.g. name of affiliation, the TITLE-ABS-KEY search was found to be of low value.

especially when the boundaries between phenomenon and context are not clearly evident. The case study research design is appropriate to test null hypotheses, as the hypothesis is regarded as false if a single case contradicts it. The first null hypothesis was generically formulated as “Adding textile chemicals will increase the environmental impact of the product”, and tested in a case study comparing bleached and unbleached night gowns. The second null hypothesis was generically formulated as “The toxicity impact potential of textile chemicals does not affect the environmental performance ranking of textile products in LCA studies”, and tested in a case study comparing two recipes for dyeing of blue cardigans.

Yin (2009) emphasizes the importance of using multiple sources of evidence to increase the quality of a case study, which is also commonly known as triangulation (Bryman and Bell, 2011; Peters et al., 2013). To answer the third research question, triangulation was applied in the second case study, to address the challenge of how to validate the toxicity assessment of textile chemicals in LCA. Three different methods by which strategic product toxicity assessment can be performed within the context of LCA were applied in the case study of a textile wet treatment process. The methods were: the USEtox consensus model (Rosenbaum et al., 2008); the Score System (European Commission, 2003); and the Strategy Tool presented by Askham (Askham, 2011). In this case study, CFs were developed for the missing textile chemicals in USEtox 1.01. For the development of the missing factors, the physiochemical properties were primarily collected from EPIsuite (USEPA, 2007), and secondarily from other sources. Toxicity properties were collected from handbooks, material safety data sheets and other public reports. The results were calculated using both recommended, interim and specifically developed CFs in USEtox and compared with the results from the Score System and the Strategy Tool.

In addition, the second case study provides information also to aspects of the third research question. The case-study setup enables the result’s dependence on the LCA practitioner’s choice of modelling to be visible, by comparing state-of-the-art LCIA to improved LCIA modelling and to the use of two simplified methods for toxicity footprint calculations.

3 Results and Discussion

This chapter contains a discussion on how the publications that this licentiate thesis is based on together with some additional material contribute to answering the research questions in Chapter 2.

3.1 Methodological frontier of LCI of chemicals in textiles

The accounting for the use and emission of chemicals is a weak point in LCA methodology and toxicity impacts are habitually excluded from LCA studies in general, as was described in section 1.2.6. The drawback of not including toxicity in environmental evaluations is especially critical in assessment of textile products since the textile industry is an intense user of chemicals. An overview of the methodological frontier of LCIA methods for chemicals was given in 1.3.2, while the methodological frontier of LCI of chemicals in textiles, addressed by the first research question, has not been explored in the literature before.

Table 3 contains an updated and more detailed version of the overview of how textile chemicals are handled in LCA studies of textiles in Paper I, and reveals large gaps in how textile chemicals have been included in LCA studies of textile products. Most of the in total 58 publications found include the issue of textile chemicals and toxicity in a qualitative way, i.e. they mention chemicals issues but do not perform a quantitative inventory of the chemicals that have been used and emitted. The seven cases where the reference is coded as “Q” have been found to contain LCI data about textile chemicals or the LCIA toxicity results for textile chemicals: the Cotton Incorporated (2012) study of cotton cultivation (as implemented in the SimaPro or GaBi softwares, LCI data is not available in the public report), the Beck et al. (2000) report on one dyestuff, one softener, one optical brightener and one sequestering agent, the Yuan et al. (2012) case study on continuous pad-dyeing of cotton with reactive dyestuffs, the Murugesh and Selvadass (2013) study on cold pad-batch dyeing of cotton with reactive dyestuffs, the Saouter and Hoof (2002) study on laundry detergents, the Schulze et al. (2001) case study on four detergents and the Hellweg et al. (2005) study on two solvents used in dry cleaning.

The columns in Table 3 have been sorted after falling share of world market for the different fibre types. Emissions of chemicals from energy production and fuel use, such as carbon dioxide and particulates, are, for the purpose of this thesis, not considered to be textile chemicals.

Table 3. Public LCA studies of textiles in the scientific and non-scientific literature. Quantitative or qualitative inclusion of textile chemicals in the publication is coded: Q = quantitative LCI in the reference, q = qualitative discussion in the publication, A = inventory including chemicals has been made but only shown as aggregated results, N/A = not applicable.

	Polyester	**Cotton**	**Poly-propylene**	**Viscose/ modal**	**Polyamide**	**Acrylic**	**Lyocell**	**Wool**	**Elastane**
Rough share of world market for fibres in 2013 (%)	42	36	9	5	4	3	1	1	1
Number of LCA studies on textiles including the fibre	21	28	2	7	8	4	2	10	2
Life cycle phase:									
Raw material extraction									
Pesticides/fertilizers	*N/A*	**Q_1**, q_3, A_2	*N/A*	-	*N/A*	*N/A*	A_4	A_5	*N/A*
Monomers and additives	A_2,q_6, A_7	*N/A*	q_6,A_7	*N/A*	A_2,q_6, A_7	A_2,q_6 A_7	*N/A*	*N/A*	A_2
Fibre spinning additives	A_2,q_6, A_7	*N/A*	q_6,A_7	q_6	A_2,q_6, A_7	A_2,q_6 ,A_7	A_4,q_6	*N/A*	A_2,q_8
Production processes									
Yarn spinning lubricants	A_2,q_8	A_2,q_8	q_8	q_8	A_2,q_8	A_2,q_8	q_8	q_8	A_2,q_8
Sizing agents	A_2,q_8	A_2,q_8	q_8	q_8	A_2,q_8	A_2,q_8	q_8	q_8	A_2,q_8
Knitting lubricants	A_2,q_8	A_2,q_8	q_8	q_8	A_2,q_8	A_2,q_8	q_8	q_8	A_2,q_8
Scouring, desizing etc.	A_2,q_8	A_2,q_8	q_8	q_8	A_2,q_8	A_2,q_8	q_8	q_8	A_2,q_8
Reactive continuous dyeing	*N/A*	**Q_9,Q_{10}**	q_8	q_8	*N/A*	*N/A*	q_8	q_8	*N/A*
Reactive exhaust dyeing	*N/A*	**Q_{11}**	q_8	q_8	*N/A*	*N/A*	q_8	q_8	*N/A*
Disperse, direct, acid etc. dyeing	q_8	q_8	q_8	q_8	q_8	q_8	q_8	q_8	q_8
Spin dyeing	q_8	*N/A*	q_8	q_8	q_8	q_8	q_8	*N/A*	q_8
Wet coating	q_8	q_8	q_8	q_8	q_8	q_8	q_8	q_8	q_8
Dry coating	q_8	q_8	q_8	q_8	q_8	q_8	q_8	q_8	q_8
Waste water treatment	q_8	q_8	q_8	q_8	q_8	q_8	q_8	q_8	q_8
Printing processes	q_8	q_8	q_8	q_8	q_8	q_8	q_8	q_8	q_8
Transport biocides	-	-	-	-	-	-	-	-	-
Use									
Exposure to skin from wearing	-	-	-	-	-	-	-	-	-
Leakage during washing	-	-	-	-	-	-	-	-	-
Wet cleaning agents	-------------------------------- A_{12},**Q_{13}**,**Q_{14}**,A_{15}--------------------------------------								
Dry cleaning agents	--------------------------------------- A_{15},**Q_{16}**--								
End of life									
Emissions from incineration, landfill leakage or recycling processes	q_{17}	q_{17}	-	-	-	-	-	-	-

Note. Q1= (Cotton Incorporated, 2012), 2012, A2 = (Velden et al., 2013), q3 = (Kalliala and Nousiainen, 1999), A4 = (Shen et al., 2010), A5 = (Barber and Pellow, 2006), q6 = (European Commission, 2007), A7 = (Boustead, 2003), q8 = (European Commission, 2003), Q9 = (Beck et al., 2000), Q10 = (Yuan et al., 2012), Q11 = (Murugesh and Selvadass, 2013), A12 = (Krozer et al., 2011), Q13 =(Saouter and Hoof, 2002), Q14 = (Schulze et al., 2001), A15 = (Keoleian et al., 1997), Q16 = (Hellweg et al., 2005), q17 =(Zamani et al., 2014).

Five publications describe the environmental impact from textiles on a general level and are not LCA studies of specific products (Beton et al., 2014; Blackburn, 2009; Farrant et al., 2010; Muthu, 2014; Slater, 2003). Of the 42 LCA studies of textiles in the literature search that were found not to include textile chemicals and toxicity, 15 included polyester textiles (BTTG, 1999; Cherrett et al., 2005; Collins and Aumônier, 2002; Dahllöf, 2004; De Saxce et al., 2012; Kalliala, 1998; Kuusinen et al., 1998; Laursen et al., 2007; Muthu et al., 2012; Shen and Patel, 2008; Smith and Barker, 1995; Steinberger et al., 2009; Thomas et al., 2012; Walser et al., 2011; Yuan, 2000). Cotton textiles were additionally addressed in ten studies (Allwood et al., 2006; Bhurtun et al., 2006; Collins and Aumônier, 2002; Dettenkofer et al., 1999; Grace et al., 2009; Güngör et al., 2009; Herva et al., 2008; Koç and Çinçik, 2010; Labouze et al., 2006; Meyer et al., 2010). The study made by Pulli et al. (1997) contains a detailed LCI for cotton wet treatment, but is only available in German and therefore not considered accessible. The other seven LCA studies of textile products, found in the literature search not to include textile chemicals and toxicity, covered other materials such as wool, linen/flax, hemp, silk or modal (Astudillo et al., 2014; Bevilacqua et al., 2011; Biswas et al., 2010; Gabarrell et al., 2012; Petiot, 2008; Terinte et al., 2014; van der Werf and Turunen, 2008). Finally, five studies had limited the scope to washing or waste management processes (Gabarrell et al., 2012; Glew et al., 2012; Hu et al., 2014; Jørgensen et al., 2004; Saouter et al., 2011).

The literature study thus reveals that the toxicity impact potential of textile chemicals is only to a marginal extent covered in LCA studies of textile products. The exclusion of textile chemicals in LCA studies of textile products can be made tacitly as in Dettenkofer et al. (1999) or explicitly as in Terinte et al. (2014), which excluded toxicity impacts and stated that the inventory data was incomplete for textile chemicals and that there was also a lack of recommended characterisation factors for specific compounds.

3.2 Effects on the environmental performance ranking of textile products from including the toxicity impact potential of textile chemicals in LCA studies

Both Paper I and Paper II discuss whether LCA can contribute to a sustainable use of chemicals in the textile industry with its quantitative approach, its life cycle perspective and its holistic view on environmental impact.

3.2.1 Life cycle perspective

Paper I demonstrated that LCA can deliver a comprehensive assessment of the life cycle environmental performance of textile products. In the case of two white hospital gowns, LCA showed to be a very useful method for evaluating the environmental impact of switching from bleached to unbleached garments. The counter-intuitive finding was that the bleached product had better environmental performance than the unbleached product, because the environmental impact from the bleaching was insignificant with regard to the whole garment life cycle and likely to be compensated by a longer lifespan in practice in the use phase of the bleached garment.

The life cycle perspective can also aid in the comprehension of the complex production chain of textile products that is not visible in the end product. The mapping of the chemicals used in the life cycle of textile garments made by the author in 2009 (Olsson et al., 2009) was an eye-opener in terms of that the weight of the chemicals used in the production phase exceeded the weight of the garment itself. The results were calculated for an optimal case (Min), an average case (Average) and a worst case (Max), and showed that the chemicals consumption is not linked to fibre choice and the raw material extraction phase, but depends to a greater extent on the processes applied in the production phase, see Figure 8.

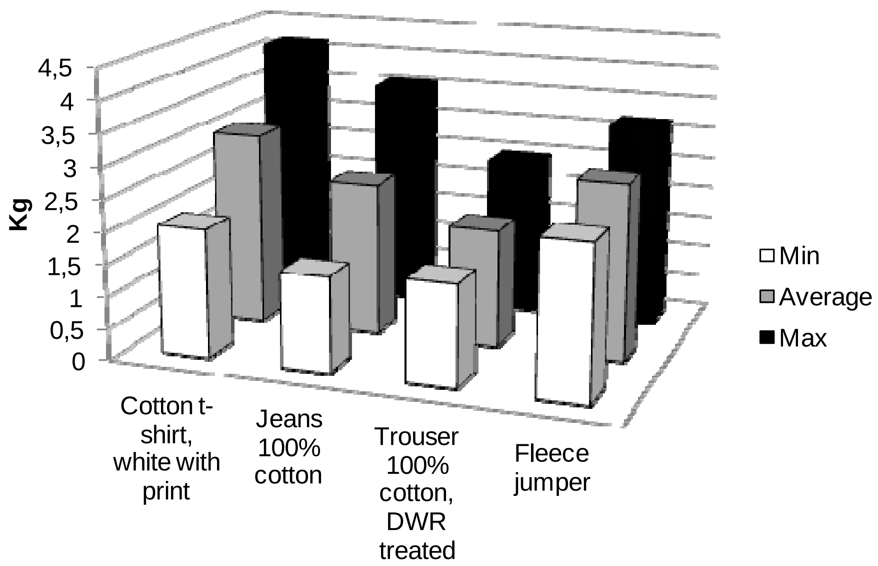

Figure 8. The variation in chemicals consumption is more dependent on the process than the material. The figure illustrates the numeric results from (Olsson et al., 2009).

3.2.2 Quantitative approach

Section 1.2.5 describes how the current main approach for evaluation of chemicals management in the textile industry is based on the evaluation of management practices, and scores are given after how well the management interventions are implemented. The complementary knowledge that can be gained from an LCA study concerns the comparative significance of the textile chemicals used during the textile product's life cycle.

A qualitative assessment entails the risk that both financial and other resources are spent on management interventions that do not contribute to any actual improvement of the environmental performance. The life cycle perspective avoids improving part of a system (for example a process or an environmental aspect) in a manner that negatively affects other parts of the system ('suboptimisation'). The case study in Paper I exemplifies this aspect where, in fact, erroneous conclusions were drawn based on intuition that unbleached garments would be more environmentally friendly than bleached ones. The quantification of toxicity impacts also shows that the choice of textile process chemicals has greater importance than the choice of dyestuffs or the addition of bleach, illustrated in Figure 9.

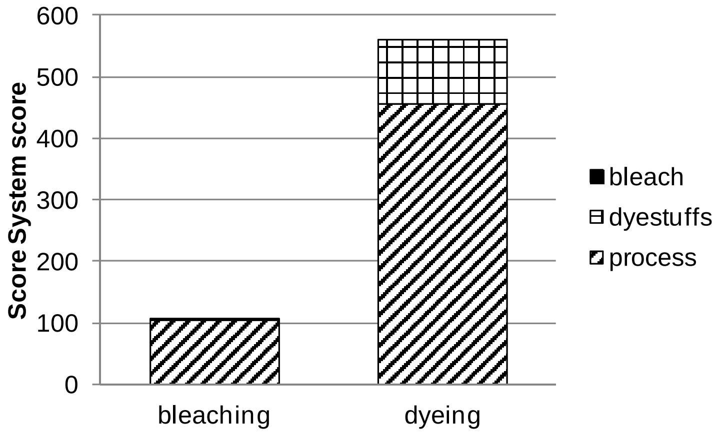

Figure 9. The comparative significance of the textile process chemicals, the bleach and the dyestuffs, calculated with the Score System. From data published in Paper I.

Paper I shows further that the inclusion of toxicity considerations of textile chemicals in LCA is likely to affect the environmental performance ranking of textile products, which is illustrated in Figure 10. In the comparison of dyestuffs for blue cardigans, serious data gaps prevented the evaluation of different dyeing options with standard LCA, and the complementary Score System was used. When extrapolating the results from the Score System back to CTUe, it was concluded that if waste water treatment (WWT) would not be in place, the baseline recipe could still have nearly the same impact as the cotton cultivation on ecotoxicity. To put this result in perspective it can be noted that conventional cotton cultivation is generally seen as one of the most polluting activities in the world, making up 25 % of the global use of insecticides on just 2 % of the global agricultural area (Kooistra et al., 2006).

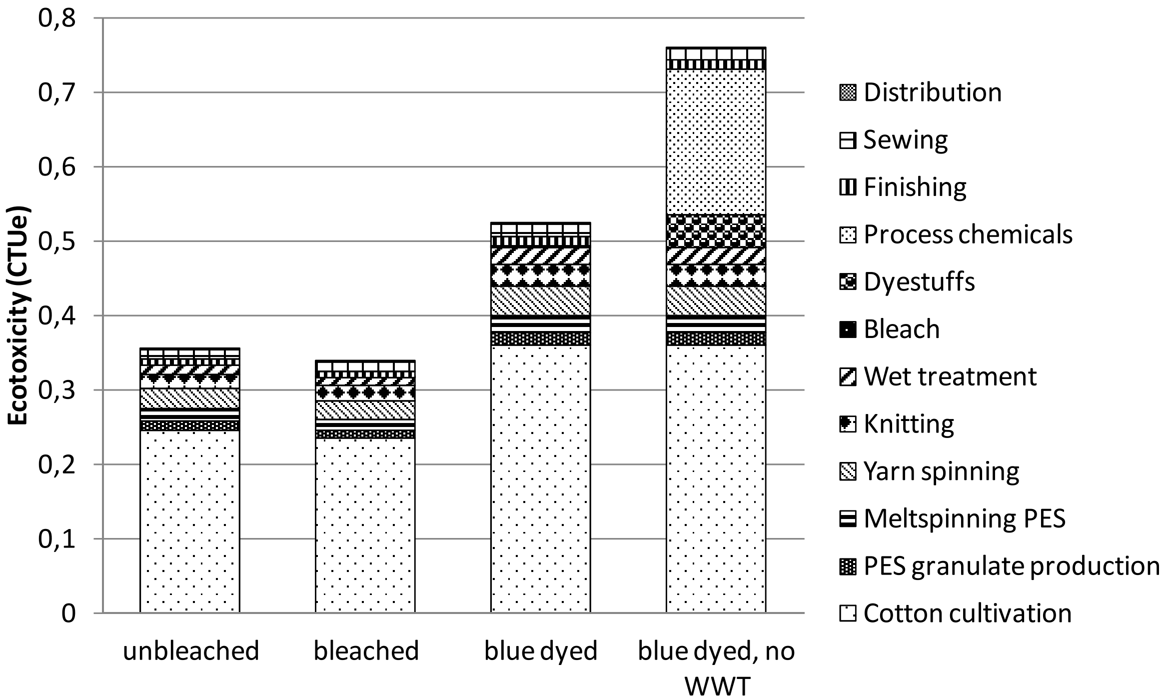

Figure 10. The extrapolated results for ecotoxicity for unbleached and bleached hospital night gowns, and for cardigans dyed blue with and without WWT.

The recommendations for action given to the textile industry's decision makers based on the conclusions from Paper I are thus to increase the lifespan of the products, optimise the choice of auxiliary chemicals and assure proper treatment of waste water in order to effectively reduce the environmental impact of the wet treatment. Avoiding the bleaching step or optimising the dyestuffs would not be effective interventions.

3.2.3 Holistic view of environmental impact

The textile industry faces a multitude of environmental challenges beside the issues with chemicals: climate change, land use, depletion of water and fossil resources (Allwood et al., 2006; Sandin et al., 2013). LCA preferably holds a holistic perspective that reduces the risk that a decision aimed at reducing pollution simply shifts the environmental problem from one environmental issue to another.

It can be noted that while in this thesis only mid-point indicators are used, which address the environmental issues described above one at the time, the LCA methodology allows for using end-point indicators such as human health, which will be affected by more than one mid-point indicator. In the example of human health, the result for this indicator will aggregate the results for climate change, human toxicity and so forth via weighting factors and thus relates the different environmental impacts to each other quantitatively. This option is useful in trade-off situations between mid-point indicators but infers a subjective standpoint to the results in the size of weighting factors and has therefore not been used in the research presented in this thesis.

3.3 Challenges with using LCA to assess the toxicity impact potential of textile chemicals

The third research question regards the main challenges in using LCA to assess the toxicity impact potential of textile chemicals. Papers I and II identify several challenges that must be overcome for LCA to be able to gain widespread use in the work towards more sustainable chemicals management in the textile industry. Paper I identified two gaps: the lack of characterisation factors for textile chemicals and the lack of access to previous studies in the area that can be used for guidance. In Paper II, the user friendliness is discussed both in terms of the work load on the LCA practitioner and the end user's understanding of and confidence in the results. The feasibility of performing a validation of the results is investigated. The challenges are discussed in more detail below.

3.3.1 Lack of previous studies to use as role models

Seven studies listed in Table 3 include textile chemicals in a quantitative way in the LCI, though the handling in the LCIA differs. Beck et al. (2000) and Schulze et al. (2001) report in detail how characterisation factors have been developed for USES-LCA, and Hellweg et al. (2005) extended the USES-LCA model to include workplace exposure. Saouter and Hoof (2002) created simplified characterisation factors for detergents that are the inverse of long term effect concentrations. The other three studies have not, or at least do not report that they have, developed any additional characterisation factors (Cotton Incorporated, 2012; Murugesh and Selvadass, 2013; Yuan et al., 2012). To be covered in the LCA, an emission of a chemical must be both listed in the LCI and have a characterisation factor, as Figure 4 in chapter 1.3.1 illustrates. The Cotton Incorporated study of cotton cultivation concerns agricultural chemicals, that have generally been better covered. Many textile chemicals in the detailed inventories in the studies of Murugesh and Selvadass (2013) respective Yuan et al. (2012) will thus render no result on the toxicity score. The limitations of the coverage of existing characterisation factors are a very important subject to discuss in the interpretation phase of an LCA (ISO, 2006b) to avoid the erroneous belief that all chemicals have been included in the result, which however seems not to be the case in these two publications. The literature is scarce on previous studies that can be used as role models.

3.3.2 Lack of inventory data and characterisation factors for textile chemicals

Paper II summarises the challenges that contribute to the lack of inventory data and characterisation factors for textile chemicals and groups them under four headings:

a) The complexity of the textile production chain. The textile production chain is very diverse in materials, processes and equipment. Both natural and synthetic materials are used and the variety of processes is also large: agricultural, chemical and mechanical processes are all

included. Each box in the schematic picture in Figure 1 contains a variety of processes and also a variety in the equipment used to perform the processes.
None of the actors along the production chain possess a complete overview of the materials, processes and equipment used in the other steps. The terminology used is different for each of the many steps in the production, and each of the materials. Communication in the supply chain is also hindered by linguistic and cultural differences. The challenge of putting together a complete LCI is immense for any LCA practitioner.

b) The large number of textile chemicals. In the Textile Auxiliaries Buyers' Guide more than 5 500 commercial products are reported, based on 400 to 600 active components (TEGEWA, 2008). Adding the pigments and dyestuffs used in textiles to this, the waste water treatment chemicals and the chemicals used in the raw material production and use phases, the list of relevant chemicals becomes long. The total number of chemicals that are applied in products have been estimated to well above 10,000 (Hauschild et al., 2011).
c) The lack of competence in chemistry among LCA practitioners. Many LCA practitioners are "non-chemists". The compilation of the inventory of input and emitted chemicals is difficult for a person who is not skilled in chemistry, especially since chemical reactions may transform the inputs during a process. Further, the effort required to determine whether a substance currently lacking a published characterisation factor should in fact have one - and if necessary, to calculate the factor - is high for a non-chemist.
d) The lack of information on chemicals due to commercial confidentiality. The life cycle inventory and impact assessment of chemical products are often further complicated by corporate confidentiality regarding the ingredients.

This complex picture makes the inventory of chemicals and development of characterisation factors close to a Catch 22 situation (a problematic situation for which the only solution is denied by a circumstance inherent in the problem). The inventory is seldom made since there are no characterisation factors for textile chemicals, which makes the work load disproportionately high for something that will not contribute to the result. At the same time, the lack of inventory data leads to ignorance about which the most important textile chemicals are, and the work load of calculating characterisation factors for thousands of chemicals without knowing the usefulness of them is difficult to motivate.

3.3.3 Limited user friendliness

Paper II discusses the practical usability of USEtox and LCA in general as tools to be used for steering the textile industry towards more sustainable chemicals management. The users can be divided into two groups: the LCA practitioners, who will perform the studies, calculate the results and draw conclusions; and the policy makers who will take decisions based on the conclusions that were drawn from the studies.

Paper II shows that the results of USEtox calculations are not only dependent on the method but also on how the LCA practitioner applies the method. Most users need some training before they can use the tools and methods correctly. Depending on the complexity of the tool the training period will vary. Musical instruments, scanning electron microscopes and LCA are examples of tools that possess a relatively high complexity. The work load on the LCA practitioner to correctly apply the toxicity assessment method must not be too high for the method to be widespread and viable. It will by definition have to be able to be used by LCA practitioners who are experts in neither chemistry nor textile technology, and the method development should take this circumstance into account.

The end users that will take action based on the conclusions from the study are for example public authorities, professional buyers, designers, production managers and NGOs. To cope with chemicals management, a hands-on tool that is useful in the daily work in the industry is needed. The end users have in common that they are usually not LCA experts. The ability for a non-expert to understand the toxicity assessment of textile chemicals in LCA is a relevant parameter that is discussed in Paper II. An evaluation method that is transparent, also to a non-expert, will be more reliable. The results can also rather easily be verified.

With PEF and other initiatives being implemented in which the toxicity of textile chemicals will be addressed in LCA with USEtox, it is important that the results are not misleading and that intended users feel confident to take actions based on the results. Benchmarking the results from different methods, as proposed in Paper II, can create such confidence – if the new method provides the same interpretation of the input data as the old method did or there is a good explanation for the difference. Paper II showed that the property of persistence is judged to have lower importance in USEtox compared to the two other methods. On the other hand, USEtox could provide additional advice compared to the two other methods: that one of the substances could in fact be more environmentally problematic than is signalled by the current classification under the European regulation on classification, labelling and packaging of substances and mixtures (CLP) (European Commission, 2008).

3.3.4 Lack of validation methods

In Paper II, calculations of a "toxic footprint" from a textile process, a wet treatment of a t-shirt, were carried out using three different methods: the USEtox consensus model (Rosenbaum et al., 2008); the Score System (European Commission, 2003); and the Strategy Tool presented by Askham (Askham, 2011). The results from the three methods lead to different conclusions about which textile chemicals have the most environmental impact. Not only were the textile chemicals that were identified as "hot spots" different, but the order of magnitude in the comparative significance also differed. The two semi-quantitative methods gave more equal importance to the textile chemicals while USEtox scores differ between chemicals by orders of magnitude.

Paper II shows that the modelling of persistence of organic chemicals in USEtox is a topic that needs further investigation. The Score System is very concerned with persistent contaminants and therefore the crease-preventing agent and the optical brightener, which are not readily biodegradable, receive high scores. The optical brightener is also the only chemical that has an environmental risk phrase score in the Strategy Tool. But the USEtox score is very low, which shows that the property of environmental persistence of organic chemicals is not considered to be as important in this method. Indeed, it has been previously noted that the inherent toxicity of the chemical, the avlogEC50[8] is the input parameter which contributes most to the freshwater toxicity in USEtox (Alfonsín et al., 2014; Igos et al., 2014).

Optical brighteners have long been considered an environmental problem in the textile industry due to their designed persistence; they are intended to be retained by textile products to provide the function of making the textile look whiter. The CLP classification of the substance in question is "Aquatic Chronic 3 (H412)" which means that it is harmful to aquatic life with long lasting effects. The advice from USEtox, that the optical brightener is not a chemical to prioritise for work with improved sustainability, seems doubtful in light of the classification and the advice from the other methods. The way degradation is modelled today in USEtox is based on degradation probability in half-lives, and multiplication factors of 1:4:9 to extrapolate degradation half-lives for water, soil and sediment compartments respectively (Rosenbaum et al., 2008). It is recommended to use data from the EPI Suite™, primarily experimental data if available and secondarily modelled data. However, Gouin et al. (2004) have shown that the persistence of more persistent chemicals is often underestimated in the EPI Suite™. The CLP classification used in the Strategy Tool, and the score on biodegradation in the Score System, are instead based on biodegradation studies using standardised test methods such as OECD 302B (European Commission, 2008).

Another difference between the methods is that the USEtox fate model calculates steady-state concentrations in the environment based on initial dilution at the local scale, transfer and dilution at a continental scale, and further transfer and dilution at the global scale (Rosenbaum et al., 2008). The

[8] Also called HC_{50}, see chapter 1.3.3.

persistence of organic chemicals is handled in these nested boxes in USEtox in terms of that the lower degradation rates of the persistent lead to higher steady-state concentrations in the model compared to degradable chemicals. Subsequently, the exposure and effects are larger for persistent chemicals since they are related to the steady state concentrations in the environment. Thus the persistence of chemicals is not treated as a single criterion for risk in USEtox but the property is integrated into the potential to cause harm.

Confidence in the results and conclusion is crucial for a scientific method, especially when used for policy making as is the intent of USEtox in the PEF initiative. As stated in the introduction, an experimental validation of environmental damage predicted in an LCA of a garment is not possible, but benchmarking of the results with experience from other competences can create confidence and/or help identify new challenges that were not previously perceived in the method.

4 Conclusions

This thesis has aimed to answer three research questions: 1) if the toxicity impact potential of textile chemicals is covered in LCA studies of textile products, 2) if the environmental performance ranking of textile products will be affected by including the toxicity impact potential of textile chemicals in LCA studies and 3) what the main challenges are in using LCA to assess the toxicity impact potential of textile chemicals.

The answer to the first research question is negative. The toxicity impact potential of textile chemicals is today only to a marginal extent covered in LCA studies of textile products. Further, the exclusion of textile chemicals is in several cases made tacitly. Given that the adverse effects of chemicals are generally considered an important environmental challenge for the textile industry, and that decision makers expect holistic assessments, the inclusion or exclusion of toxicity in environmental assessments of textile products is crucial.

The research results for the second research question show that the total environmental performance ranking of textile products can be affected by including the toxicity impact potential of textile chemicals in LCA studies. The life cycle perspective in LCA showed in Paper I to be useful for evaluating the environmental impact of switching from bleached to unbleached garments. The counter-intuitive finding was that the bleached product had better environmental performance than the unbleached product, because of the longer lifespan in the use phase of the bleached garment. Also, quantification of toxicity impacts in LCA allows for revealing the comparative significance of chemicals. The choice of textile process chemicals seems to have greater importance than the choice of dyestuffs (see Paper I), in contradiction to the large focus that today is put on choice of dyestuff in the textile industry. The holistic perspective of environmental impact in LCA reduces further the risk that a decision aimed at reducing pollution simply shifts the environmental problem from one environmental issue to another. LCA can thus contribute to improved environmental performance ranking of textile products with its life cycle perspective, its quantitative approach and its holistic view on environmental impact.

The third research question has a descriptive character. Several challenges have been identified which must be overcome for LCA to contribute to the sustainable use of chemicals in the textile industry. The assessment of toxicity impact potential of textile chemicals within the LCA context is in itself a difficult task, requesting knowledge about textile processes and chemistry from the LCA practitioner. In addition to the broad scope of competence required, the complexity of the textile production chain and the diversity in both use and properties of textile chemicals are challenging. There is very little guidance in the area in the literature today. There is also a lack of validation methods that can be used in order to corroborate the results from the LCA study and make the end user confident in taking action towards more sustainable use of chemicals in the textile industry, which is the main purpose of performing the LCA study.

In order to accomplish the goal set up at the Johannesburg World Summit, a strategy for sustainable use of chemicals is needed in the textile industry. This strategy should enable substitution of hazardous chemicals, improve control of the use of chemicals and, most importantly, encourage action from the stakeholders. The main advantage of using LCA to assess the toxicity impact potential of textile chemicals, compared to the today common management focused evaluation procedures, is that there is potential for the actual environmental performance to be quantitatively measured. When correctly performed, the quantitative toxicity assessment that is carried out in an LCA allows for comparison of the effectiveness of different chemicals management interventions. Thus LCA can guide product procurers, designers and other environmental decision makers to take environmentally sound decisions.

5 Recommendations and Future Research

LCA can, if the challenges described in chapter 3.3 are addressed, contribute to a sustainable use of chemicals in the textile industry with its quantitative approach, its life cycle perspective and its holistic view of environmental impact. Future research should be focused on developing an interdisciplinary nomenclature for chemicals and technology that can be used in all four phases of the LCA methodology; goal and scope formulation, life cycle inventory, life cycle impact assessment and interpretation, and by all the three different expert competences that are needed; LCA, textile technology and chemistry.

Although the number of chemicals used in the textile industry is large, this nomenclature should be possible by applying a function-based chemicals categorisation. In order to understand and predict the presence of chemicals in materials and products, different categories can be defined depending on the reason behind their presence in a certain material or product, i.e. the function. On the basis of this philosophy, three main categories of chemicals are proposed to be distinguished namely:

- Chemicals produced by humans or nature with certain functionality/ies in the final product, mentioned as functional chemicals – often detected in high concentrations in the product.
- Chemicals produced by humans or nature with no functionality/ies in the final product, mentioned as residues from the production processes or impurities – seldom detected in high concentrations in the product.
- Chemicals that occur through unintended production by humans or nature, mentioned as impurities – never detected in high concentrations in products.

The development of this function-based chemicals categorisation started in 2004 with the insight from the Swedish Chemicals Agency project INKA (Swedish Chemicals Agency, 2004) that the communication around the chemical content of products was not adequate to protect consumers or the environment from being exposed to hazardous substances. The functional chemicals approach has the advantage that it provides the link between on the one hand the quality and technical properties of a product that are specified by the companies, and on the other hand the chemistry used in the supply chain and therefore enables companies to control the latter. A nomenclature development based on the functional chemicals approach can be used to support LCI made by LCA practitioners and commercial LCA databases to include the most significant chemicals in terms of environmental and health impact in the life cycle of textile products. LCIA methods need in their turn to cover textile relevant chemicals, and development of CFs need also be based on this function-based chemicals categorisation to match the LCI.

Other areas of recommended future research include taking steps towards determining planetary boundaries for chemical pollution as defined by Rockström et al. (2009) and improving the fate modelling of persistent chemicals in LCA. Such research could be very relevant for the textile industry considering that many property lending textile chemicals are organic persistent chemicals. Improved fate modelling may include detailed research of the limitations in applicability of the EPI Suite™ software for persistent chemicals, the consequences of the steady-state approach for persistent chemicals and/or method development for increased confidence in the toxicity impact assessment results.

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