THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Advancing life cycle assessment of textile products to include textile chemicals

Inventory data and toxicity impact assessment

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Gothenburg, Sweden 2016

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Inventory data and toxicity impact assessment.
SANDRA ROOS
ISBN 978-91-7597-521-4

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Doktorsavhandlingar vid Chalmers tekniska högskola
Ny serie nr 4202
ISSN: 0346-718X

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Cover: Storage of fabrics after wet treatment. Picture by the author.

Chalmers Reproservice
Gothenburg, Sweden 2016

Advancing life cycle assessment of textile products to include textile chemicals. Inventory data and toxicity impact assessment.

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Abstract

Textile products are used by almost everybody throughout the world, fulfilling basic human needs such as keeping us warm and contributing to our social position. Every year the global textile industry delivers close to 100 million metric tonnes of new products to the market. The volume of products gives a hint also to the magnitude of the environmental burden of the textile industry.

The major environmental impacts of textile products arise from emissions of toxic substances and use of water and energy in the production phase of the life cycle. Among these, impacts from emissions of toxic substances are particularly difficult to assess. In this thesis life cycle assessment (LCA) is used to study the environmental impact of textile products. The holistic perspective of LCA reduces the risk that new solutions for textile production technology, aimed at reducing pollution, will simply shift the environmental impact from one life cycle phase to another, or from one type of environmental impact to another. The objective of the research has been to develop LCA methodology for assessing toxicity impacts so that LCA can provide holistic guidance towards improving the environmental performance of textile products. However, LCA face challenges concerning both inventory and modelling of toxicity impacts of textile chemicals.

Three research questions are answered: (1) does LCA provide additional knowledge regarding toxicity impacts compared to other less time-consuming environmental assessment methods, (2) which LCA data gaps are most important to fill in order to cover the most common processes and chemicals in the textile industry, and (3) can methodology be developed to fill prioritized LCA data gaps at a reasonable demand of time and competence?

It is concluded that the main benefit of using LCA to assess the toxicity impact of textile chemicals lies in the potential for expressing the environmental performance quantitatively, in comparison to qualitative, semi-quantitative and management routine-focused methods. The thesis presents a framework for systematizing the life cycle inventory of textile processes and methodology for matching the inventory results with characterisation factors in the impact assessment. The framework includes a set of 30 life cycle inventories of common textile processes. The framework, methods and life cycle inventories are transparently documented in order to enable inclusion of additional processes in the future.

Keywords: Life cycle assessment, LCA, Textile, Chemicals, Impact assessment, Toxicity, Inventory

Acknowledgements

I would like to gratefully acknowledge all those people who have made it possible for me to write this thesis. During these five years of research I have received advice, knowledge, insights, daring, inspiration and support from so many people, and it is impossible to list all of you.

I would like to thank my main supervisor, Anne-Marie Tillman, as well as my co-supervisors at Chalmers, Rickard Arvidsson and Magdalena Svanström, for attentive and patient guidance towards making this work a complete entity. My co-supervisors at Swerea, Christina Jönsson and Anna Karin Jönbrink, together with Stefan Posner have provided mentorship, collaboration and have given invaluable input and support to this work. Thank you!

I have also been very lucky to have great colleagues to work with in projects, in my group at Swerea IVF and at Chalmers as an industrial PhD student. I would like to thank my co-authors; Hanna Holmquist, Bahareh Zamani, Gustav Sandin and Greg Peters. It has been instructive as well as joyful to see the papers develop from our common struggle.

I also gratefully acknowledge the financial support from the Swedish Foundation for Strategic Environmental Research (Mistra) via the Mistra Future Fashion programme and the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (Formas) via the SUPFES project.

Finally, I would like to thank all of my beloved family and friends for giving me support and being there for me. Special thanks to David, Jonathan and Erik.

Appended papers

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

I. Roos, S., Posner S., Jönsson C., Peters G. (2015) Is unbleached cotton better than bleached? Exploring the limits of life cycle assessment in the textile sector, Clothing and Textiles Research Journal, Vol. 33 (2015), 4, pp. 231-247

II. Roos, S., Peters, G. (2015) Three methods for strategic product toxicity assessment – the case of the cotton t-shirt. The International Journal of Life Cycle Assessment, Volume 20, Issue 7, pp 903-912

III. Roos, S., Zamani, B., Sandin, G., Peters, G.M., Svanström, M. (2016) A life cycle assessment (LCA)-based approach to guiding an industry sector towards sustainability: the case of the Swedish apparel sector, Journal of Cleaner Production, Volume 133, 1 October 2016, pp. 691–700

IV. Roos, S., Holmquist, H., Jönsson, C., Arvidsson, R. USEtox characterisation factors for textile chemicals based on a transparent data source selection strategy, submitted manuscript

V. Roos, S., Jönsson C., Posner S., Arvidsson, R., Svanström, M. A systematic life cycle inventory framework for inclusion of textile chemicals in life cycle assessment, manuscript in preparation

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.

Paper III

The author performed the major part of the research design, modelling and writing concerning environmental life cycle assessment, while the social life cycle assessment part was mainly conducted and written by Dr. Zamani and Prof. Svanström. The industry sector approach was developed together with the second and third authors and the article was written with feedback from all co-authors.

Paper IV

The author performed the research design, did the modelling together with Lic.Eng. Hanna Holmquist and wrote the article with feedback from all co-authors.

Paper V

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

Related contributions

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

1. Schmidt, A, Watson, D, Roos, S, Askham, C, Brunn Poulsen, P (2016) Life Cycle Assessment (LCA) of different treatments for discarded textiles. TemaNord 2016:537. Nordic Council of Ministers. Copenhagen.
2. Roos, S, Zamani, B, Sandin, G, Peters, GM, Svanström, M (2016) Will clothing be sustainable? Clarifying sustainable fashion, Chapter 3 in Muthu, SS, Textiles and Clothing Sustainability - Implications in Textiles and Fashion. Springer Singapore
3. Roos, S, Jönsson, C, Posner, S, Peters, GM (2015) Simultaneous development of inventory and impact assessment enables chemicals inclusion in textile LCA, proceedings from the 7th International Conference on Life Cycle Management, 30th August – 2nd September 2015, Bordeaux, France.
4. Roos, S, Sandin, G, Zamani, B, Peters, GM, Svanström, M (2015) Clarifying sustainable fashion: Life cycle assessment of the Swedish clothing consumption, proceedings from the 7th International Conference on Life Cycle Management, 30th August – 2nd September 2015, Bordeaux, France.
5. Sandin, G, Roos, S, Zamani, B, Peters, GM, Svanström, M (2015) Using the planetary boundaries for evaluating interventions for impact reduction in the clothing industry, proceedings from the 7th International Conference on Life Cycle Management, 30th August – 2nd September 2015, Bordeaux, France.
6. Strömbom, S, Posner, S, Roos, S, Jönsson, C (2015) Chemicals management in the textile sector – Dialogue between authorities, research institutes and retailers leading to concrete actions, proceedings from the 7th International Conference on Life Cycle Management, 30th August – 2nd September 2015, Bordeaux, France.
7. Roos, S, Sandin, G, Zamani, B, Peters, GM (2015) Environmental assessment of Swedish fashion consumption. Five garments - sustainable futures. Mistra Future Fashion report. Stockholm, Sweden.
8. Peters GM, Svanström M, Roos S, Sandin G, Zamani B (2015) Carbon footprints in the textile industry. Chapter 1 in Muthu, SS, Handbook of life cycle assessment (LCA) of textiles and clothing. Woodhead Publishing/Elsevier. Cambridge UK.
9. Roos, S, Peters, GM (2015) Validation of the results from toxicity assessment in LCA using triangulation, proceedings from the SETAC Europe 25th Annual Meeting, 3-7 May 2015, Barcelona.
10. Roos S, Posner S, Jönbrink, AK (2011) 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. Stockholm.
11. Olsson E, Posner S, Roos S, Wilson K (2010) ”Kartläggning av kemikalieanvändning i kläder” [Mapping chemicals use in clothes], Swerea IVF report 09/52 (2010) on commission of Swedish Chemicals Agency. Kemikalieinspektionen. Stockholm.

List of abbreviations

avlogEC50	Hazardous concentration for 50% of species
ADHD	Attention Deficit Hyperactivity Disorder
BAF_{fish}	Bioconcentration factor for fish
BAT	Best Available Technology / Best Available Techniques
BEP	Best Environmental Practices
BCF	Bioconcentration Factor
BOD	Biochemical Oxygen Demand
CF	Characterisation Factor
CLP	Classification, Labelling and Packaging of substances and mixtures (European Regulation (EC) No 1272/2008)
COD	Chemical Oxygen Demand
CTUe	Comparative Toxic Unit for ecotoxicity
CTUh	Comparative Toxic Unit for human toxicity
EF	Effect Factor
ILCD	International Reference Life Cycle Data System
IPCC	Intergovernmental Panel on Climate Change
KdegW	Degradation rate in water
K_{DOC}	Dissolved organic carbon/water partition coefficient
K_{OW}	Octanol/water partition coefficient
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory analysis
LCIA	Life Cycle Impact Assessment
MSDS	Material Safety Data Sheet (also termed Safety Data Sheet, SDS)
NGOs	Non-Governmental Organisations
NMVOC	Non-Methane Volatile Organic Compounds
NPEO	Nonylphenol ethoxylates
PEF	Product Environmental Footprint
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctane sulfonate
pKa	Acid dissociation constant
POP	Persistent Organic Pollutants
RAPEX	European Rapid Alert System for non-food dangerous products
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals (European Regulation (EC) No 1907/2006)
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

The risk of surpassing thresholds of the Earth's carrying capacity in several aspects of environmental sustainability (climate change, biodiversity, chemical pollution etc.) is well explained by the concept of planetary boundaries (Rockström et al., 2009). According to the planetary boundary framework, human perturbation of two of the planetary boundaries (genetic biodiversity and biogeochemical flows of nitrogen and phosphorus) are already beyond the zone of uncertainty, which means there is high risk for destabilization of the Earth's system at the planetary scale. In addition, it is unknown whether some planetary boundaries have been surpassed or not. Chemical pollution is one such boundary, together with novel entities in general, atmospheric aerosol loading and functional biodiversity (Steffen et al., 2015). Such alarming reports call for action as the environmental pressure on the Earth needs to be reduced.

Strategies for reducing the environmental pressure on the Earth differ between organizations, industry sectors and countries. The strategies are sometimes categorised according to the so-called IPAT equation (Alcott, 2010), introduced in a discourse between Commoner, Ehrlich, and Holdren in the 1970s (Commoner, 1972; Ehrlich and Holdren, 1972):

$$I = P \times A \times T \qquad \text{(Eq. 1)}$$

where the unwanted environmental Impact (I) depends on Population size (P), Affluence (A; the consumption of goods and services per person) and Technology (T; the environmental impact per the amount of goods and services). The global population is projected to continue to grow, passing 11 billion people before year 2100 (United Nations, 2015), albeit at a decelerating rate. It therefore does not seem likely that the P factor in the IPAT equation will be reduced in the imminent future. In order to stay within the planetary boundaries, the reduction of environmental impact will then be dependent on reduced consumption of services and goods and/or improved technology.

The topic of this thesis is environmental impact caused by textile products. Both apparel and home textiles are used by almost everybody throughout the world, fulfilling basic human needs such as keeping us warm and contributing to our social position. The textile industry is one of the world's largest industries, with a total share of around 4% of the global merchandise trade (World Trade Organization, 2015). Textile products also contribute to a significant share of the environmental burden on the Earth.

How much the Affluence (A) factor of the IPAT equation can be reduced regarding textile products can be discussed. In 1987 Manfred Max-Neef presented nine basic human needs that are universal, unchanging over time and where one cannot replace any other (Boulanger et al., 2010). These are: subsistence, protection, affection, understanding, participation, leisure, creation, identity and freedom. Textiles can contribute to meeting all of these needs (Roos et al., 2016). For example, clothing helps us meet the need for understanding as it signals rank and responsibility (e.g. military and hospital uniforms), it marks cultural occasions (e.g. weddings, funerals and festivities) and can be used to express opinions, religion and so forth. In western society consumerism is a strong characteristic of the culture. Consumption of clothing ("shopping") can sometimes itself be used to fulfil the need for signalling identity, either by contributing to group belonging or to the feeling of self-uniqueness (Lynn and Harris, 1997). Fashion trends change every season, which encourages consumption. The consumption of textiles is therefore expected to increase, not only because the global population is increasing but also because consumerism is likely to spread. In the current society the Population size (P) and Affluence (A) factors of the IPAT equation can only be reduced so much if the social well-being, the fulfilment of basic human needs, is not to be reduced. It is thus clear that technology solutions for reducing the environmental impact of textile products must be developed to also address the Technology (T) factor of the IPAT equation.

The research presented in this thesis deals with environmental assessment of different technology solutions for reducing the environmental impact of textile products. A focus has been placed on toxicity impacts caused by emissions of textile chemicals. Before presenting the purpose and scope of the research in section 1.3, section 1.1 gives an introduction to the textile life cycle, with its long and complex supply chain, during which most of the environmental impact of textiles has been shown to occur (European Commission, 2003). A large variety of emerging textile production technologies have been proposed as solutions for reducing the environmental impact of textile products, which will also be presented in section 1.1. To be able to identify which of the solutions will be most effective in reducing the environmental impact some kind of assessment method needs to be used. This is discussed in section 1.2, together with the rationale for using life cycle assessment (LCA) for assessing the environmental performance of textile products.

1.1 Textiles and the environment

The textile industry is one of the world's largest industries, as mentioned above. Every year the global textile industry delivers close to 100 million metric tonnes of new products to the market (The Fiber Year, 2014). The large volume of products gives a hint also to the magnitude of the environmental burden of the textile industry.

Figure 1 aims to illustrate the complexity of the globalized textile industry and its environmental impacts, with a focus on impacts from chemicals. Textile production, which is further explained in section 1.1.1, involves a multitude of production processes, each performed by different actors (Kogg, 2009). From the European perspective, the fact that textile production processes are geographically located mostly outside the European continent adds additional challenges to the environmental management of textile products.

The major environmental impacts of textile products arise from the textile production part of the life cycle, of which the most important impacts are related to the use and emissions of toxic chemicals, as well as the use of water and energy (with related greenhouse gas emissions leading to climate change) (Allwood et al., 2006; European Commission, 2003; Roos et al., 2015).

Cotton cultivation is one of the most problematic processes in the textile production chain. Conventional cotton cultivation is both water- and chemical-intensive, and a lot of initiatives are taken by the textile industry to improve this situation, including the Better Cotton Initiative (BCI, 2013) and the Global Organic Textile Standard (GOTS, 2011). Cotton cultivation occupies less than 2.5% of the world's arable land but uses 11% of the world's agricultural chemicals, mostly fertilizers, insecticides and herbicides. Looking only at insecticide use, cotton cultivation accounts for 25% of the global consumption (Bärlocher et al., 1999). The use of water for irrigation of cotton fields is also a hotspot in the textile supply chain; the production of cotton demands roughly 10,000 litres of water per kg cotton and the cultivation is often located in water-scarce areas (Kooistra et al., 2006). The 1960s large-scale irrigation campaign aimed at achieving independence in cotton production in Soviet Central Asia caused the desertification of the Aral Sea, with disastrous environmental consequences (Saiko and Zonn, 2000).

Wet treatment (bleaching, dyeing, finishing) is another infamous source of the environmental impact of textiles (European Commission, 2003; Hasanbeigi and Price, 2015). It is both energy-, water- and chemical-intensive. To produce 1 kg of garment today it has been estimated that between 1.5 and 6.9 kg of chemicals are 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). Not all textile chemicals are toxic, but some are, and emissions of toxic chemicals from textile production have been highlighted by several non-governmental organizations (NGOs) in recent years. One example is the Greenpeace Detox campaign (Brigden et al., 2012), leading to the Zero Discharge of Hazardous Chemicals (ZDHC, 2014) initiative from the textile industry.

Depending on the local context, the consumers' transport to and from the store, laundry processes and waste management may also make a considerable contribution to the environmental impact of textiles (Roos et al., 2016).

The social conditions of textile production have also started to receive a lot of attention during the past decade (Chi, 2011; Zamani, 2016). This aspect is however not covered in this thesis.

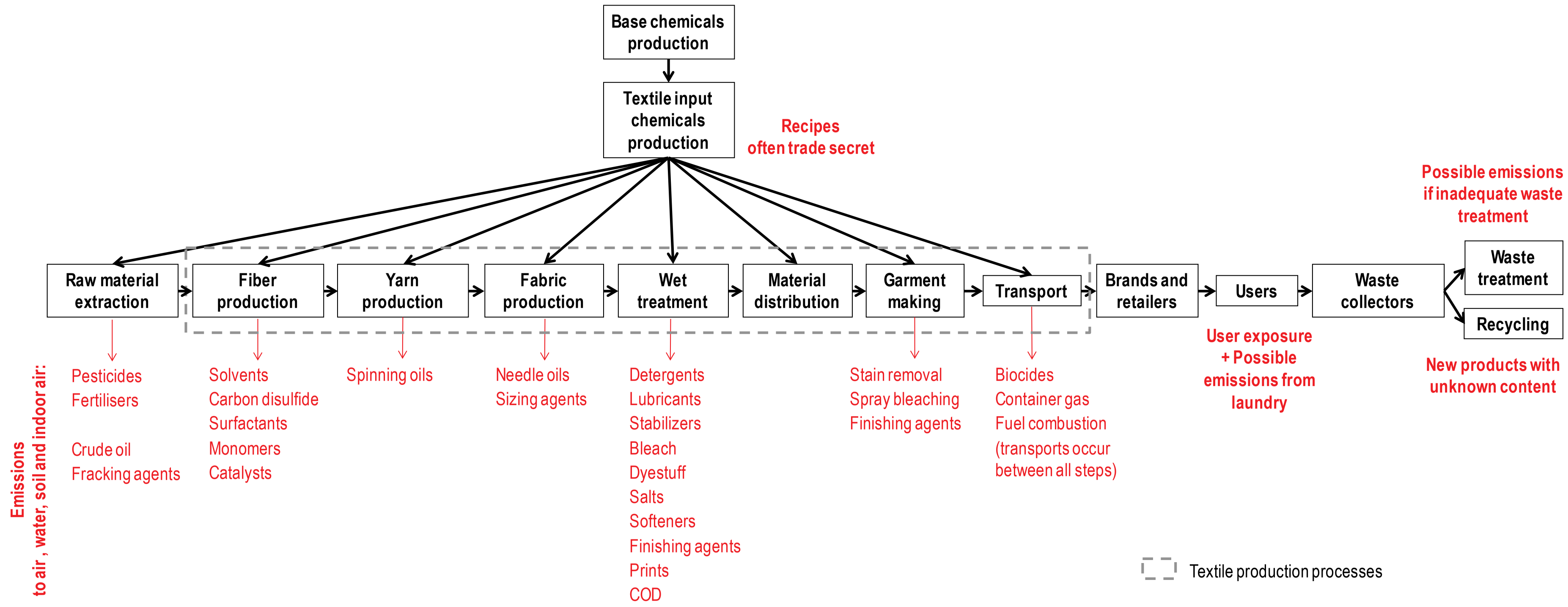

Figure 1. Schematic picture of chemicals-related challenges (in red) in the textile life cycle. The most common situation today is that textile production processes (within the dashed line) are geographically located outside the European continent, which adds an additional supply chain communication challenge. Finishing agents are e.g. biocides, flame retardants, water/oil repellents etc.

1.1.1 Textile production

Each step of textile production involves a variety of materials, processes and equipment. The types of processes involved vary from agriculture and animal farming for fibres to chemical processing and mechanical operations. The textile production processes from fibre to garment (from left to right in Figure 1) are briefly described below. The aim of this section is to provide an overview of textile materials and concepts, while a more thorough understanding of textile production can be gained from textbooks on the subject (e.g. Humphries, 2009) or the Reference Document on Best Available Techniques for the Textiles Industry (European Commission, 2003).

Fibre production

Fossil-based synthetic fibres, such as polyester, polyamide and elastane, make up around 60% of the fibres on the market, with bio-based cotton fibres representing around 35%. Other bio-based fibres, such as viscose, lyocell, wool, silk, flax and synthetic fibres from bio-based raw materials, together have a market share of roughly 5% (The Fiber Year, 2014). Cotton, wool, silk and flax are examples of natural fibres, i.e. the long and thin fibre shape is created by nature. Cotton is thus already in the shape of fibres when harvested, manually or by machine, and is then ginned, which means that the lint and seed are separated. Synthetic and regenerated fibres are in contrast manufactured from plastic granulates or pulp, which is then given its fibre shape by extrusion via a nozzle, termed fibre spinning. There are different types of fibre spinning technologies; regenerated cellulose fibres (viscose and lyocell) are wet spun, polyester and nylon are melt spun, while elastane is dry spun. The fibre spinning that creates fibres should not be confused with yarn spinning that creates yarn, which is described in the following section.

Yarn production

Synthetic fibres are produced as filament fibres and can be texturized and drawn into filament yarns or cut into staple fibres (usually 38 mm) to produce spun yarn, depending on the application. Regenerated cellulose fibres are as a rule used in garments as spun yarn from staple fibres. All natural fibres (except silk) are harvested as staple fibres and spun to yarn. The spinning of yarn from staple fibres can be made from a single fibre material or a fibre mix. The spinning is followed by a twisting step, which is necessary to achieve a yarn that will resist the pressure applied during weaving or knitting.

While the thickness of the fibre (often measured as denier or dtex[1]) is fixed for natural fibres, synthetic and regenerated fibres can have various thicknesses. The yarn size depends on both fibre thickness and number of filaments, which affects the feel of the fabric (from soft microfibre yarn to coarse yarns). The yarn size also affects the use of energy and chemicals in the subsequent production steps.

Fabric production

Fabrics are either woven, knitted or nonwovens. Most fabrics are produced from what is known as grey yarn, which is yarn that has not been bleached or dyed. If the fabric will be patterned (for example chequered or denim weave), the yarn is bleached and dyed before fabric production.

Weaving generally requires yarns of good strength, especially for the warp yarn, while the weft yarn is subject to less tension. Before weaving the yarns are sized, which means they are

[1] 1 denier (den) = 1 g/9,000 m. 1 dtex = 1 g/10,000 m.

lubricated in order to reduce the wear on the yarn during the weaving process. The produced weave therefore needs to be desized (washed and dried) afterwards, which is done at the weaving plant or at a wet treatment facility.

The knitting process depends on the gauge of the tricot, or in other words the number of stitches per inch. Circular knitting is used for high gauges and flat knitting is used for low gauges. Fully fashioned knitting is also becoming increasingly common, where the garment is shaped already in the knitting machine.

Nonwovens are not made via yarn but are instead produced directly from fibres, either from staple fibres or directly from filaments. To increase the fabric strength, bonding with a resin or needle-punching can be performed.

Wet treatment

The dyehouse performs the wet treatment of fabrics, which includes pre-treatment, dyeing and finishing, and sometimes also printing.

Pre-treatment includes mainly desizing, washing, scouring, and bleaching. Scouring removes natural impurities from the cotton, such as pectins, hemicellulose, waxes and debris. Pre-treatment removes metal ions and other substances that will otherwise have a negative impact on the following steps. Bleaching (only for natural fibres) adds to the removal of impurities, increases the efficiency of dyeing and gives the desired appearance to non-dyed products.

The type of dyestuff and auxiliary chemicals applied depends on the fibre. For cellulose fibres, such as cotton, reactive dyes, vat dyes and direct dyes can be used. For synthetic fibres such as polyester and nylon, disperse dyes, acid dyes or vat dyes are used instead. Cellulosic materials are often dyed at 60-80°C, while synthetic fibres are dyed at higher temperatures, i.e. 100-135°C.

Finishing includes wet process steps (colour fixation, neutralisation, and addition of finishing agents, such as softeners, water-repellents or flame retardants), but also drying, dimensional fixation, sanforisation (to reduce fibre tension) and coating.

Wet treatment of fabric can be performed using various machinery, for example continuous pad dyeing machines, pad batch dyeing machines, jet/air-jet dyeing machines and jiggers. The choice of machinery depends on the type of fabric and the production scale. Wet treatment of yarn is performed in bobbin dyeing machines, and sometimes in hank dyeing machines. For wet treatment, technology is evolving fairly quickly in order to reduce environmental impact. Emerging technologies include for example super-critical CO_2-dyeing and spin-dyeing and are further described under 1.1.3.

Printing is sometimes made on the fabric at the dye-house, and sometimes on the garment at the sewing factory. Printing can be performed as roller print, screen print, transfer prints, etc. The pigments and dyestuffs are selected based on the fibre material, just as with dyeing. In recent years the use of digital printing techniques have been increasing, enabling highly adapted pattern printing.

Garment making
The confectioning of a garment includes cutting, sewing, ironing and packaging, and sometimes also garment finishing (garment wash, denim bleach, printing, etc.).

The garment makers (also called sewing factories) are the tier 1 (direct) supplier to the brands and retailers in Figure 1, although it is very common for European actors to work through agents instead of having direct contact with the garment makers.

1.1.2 Textile chemicals

The focus of this thesis is toxicity impacts caused by use and consequently emissions of textile chemicals. The term textile chemical is used throughout this thesis for a chemical that is directly applied to the textile in any part of its production processes (excluding fibre cultivation and the use of the textiles). Textile chemicals can be pure substances, or more commonly, mixtures of substances.

The Venn diagram in Figure 2 shows how the term textile chemicals exclude non-textile specific agricultural chemicals, such as pesticides and fertilizers, as well as use phase detergents and softeners added by consumers. Furthermore, other emissions occurring during the textile life cycle, such as exhaust gases from fuel combustion and leakage of substances from mining waste, are not considered to be textile chemicals. The term textile chemical also excludes transformation products, which are substances that are either formed by intended or unintended chemical reactions involving textile chemicals, or products from the degradation of textile chemicals in the environment and human body. Impurities, which are the contents of chemical products that are contaminants and are not produced during the production process in question, as well as residuals, which are substances that are produced during the production process as by-products or as unreacted starting material, can occur in textile chemicals in small amounts. Transformation products, impurities and residuals are not considered textile chemicals but are textile-related substances. As such, they are also within the scope of this thesis.

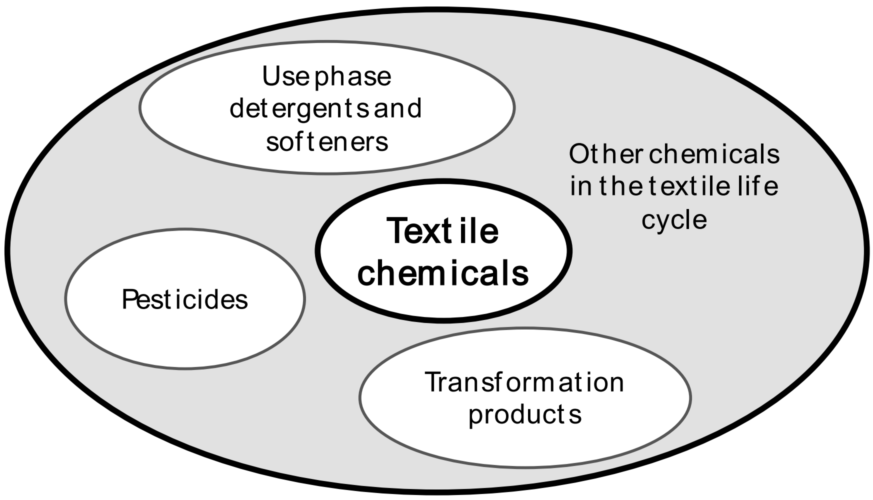

Figure 2. Delimitation of the term textile chemical. For the purpose of this thesis, textile chemicals are defined as the chemicals in the textile life cycle that are directly applied to the textile in any part of its production processes. The figure is presented for illustrative purposes and does not show a complete picture of the chemicals in the textile life cycle.

Examples of impacts of textile chemicals

Textile products are worn by almost everybody throughout the world, from newborn babies to sick and sensitive persons, and are often in direct contact with the skin. The occurrence of toxic substances in textiles, such as allergens and endocrine disrupters, is therefore disturbing. Textile products further cause exposure of the workers in the textile supply chain to toxic substances, as well as emissions to the environment. Some of the most highlighted textile chemicals that are problematic to humans and the environment are per- and polyfluoroalkyl substances (PFAS), nonylphenol ethoxylates (NPEO) and phthalates (Stenborg, 2013).

Textile applications for PFAS-based chemicals are mostly water- and oil-repellent properties on outdoor garments (so called durable water repellent (DWR) treatment), but they are also used in digital printing processes to prevent bleed-through of the fabric. PFAS are or transform into persistent substances, meaning that they resist degradation in the environment. They also bioaccumulate, meaning that their concentration in organisms can become higher than that of the surrounding environment. Such substances have been detected in the blood of small children, adults and other mammals, as well as in the ground and water in remote areas, such as the Arctic (Posner et al., 2013). PFAS have been linked to adverse health effects, such as low birth weight, delayed puberty onset, elevated cholesterol levels, reduced immunologic responses to vaccination and over-representation of ADHD in children (Bergman et al., 2013).

NPEOs are a commonly occurring group of surfactants used in all steps of the textile supply chain, although mainly in the wet treatment as detergents, dispersants and emulsifiers. In the environment NPEO breaks down to nonylphenols, which are both endocrine disrupters and environmental toxins (ECHA, 2013). Fish are especially sensitive to nonylphenol exposure, which has been shown to impair reproduction as well as complete sex reversal of three different fish species, resulting in all-female populations. Effects observed also include behavioural effects that may influence the gene pool (Swedish Chemicals Agency, 2014). NPEO is categorised as a textile chemical in this thesis and nonylphenols are categorised as textile-related substances.

Phthalates are textile chemicals used as plasticizers in polymeric materials and occur in textile products in trimming details, prints and artificial leather. Foetuses exposed to phthalates show effects on reproductive organs and fertility, such as increased nipple retention, decreased anogenital distance and increased incidence of genital malformations, delayed puberty onset as well as reduced semen quality (ECHA, 2016).

Management of textile chemicals

Section 1.1 introduced the management challenge caused by the textile supply chain being to a large extent situated outside countries where most textiles are used. When it comes to the management of chemicals this challenge becomes even more obvious. Substances that are restricted within the European Union (EU) in textile products may be legal to use in the producing countries. From the European legal perspective there are two groups of PFAS (PFOS, perfluorooctane sulfonate and PFOA, perfluorooctanoic acid) that are regulated in textiles; PFOS-related substances are classified as Persistent Organic Pollutants (POP) and are regulated by the Stockholm Convention (UNEP, 2016) and PFOA-related substances are regulated in Norway (Norwegian Environment Agency, 2013). In addition, many textile companies have voluntary phase-out programs for other PFAS. NPEO will be restricted in textiles from 2021 in the EU under the European chemicals legislation REACH (European Commission, 2006), but NPEO is currently subject to voluntary phase-out programs by textile companies. Most countries, including those within the EU, have restrictions on the use of phthalates in toys and childcare articles. However, no phthalates are currently legally restricted in textiles in the EU. A restriction of four phthalates in products for indoor use or with skin contact was however proposed in 2016 (ECHA, 2016).

Considering the severe health and environmental effects that many textile chemicals and their transformation products can cause, exemplified here by PFAS, NPEO and phthalates, the voluntary work that the textile industry does to avoid using these legally allowed chemicals is important. Since the concentrations of toxic substances in the products imported to the EU are usually low or below detection limits, the main risks related to textile chemicals are rather exposure of the workers in the textile supply chain, as well as emissions to the local environment in the producing countries (Swedish Chemicals Agency, 2015).

Figure 1 shows some of the terms of the functions that textile chemicals provide; detergents, bleach, biocides, needle oils etc. A division according to these functions can be made into chemicals that provide desired properties to a garment (Swedish Chemicals Agency, 2004), "effect chemicals" (colour, anti-odour properties, soft hand etc.), and chemicals that provide desired properties to production processes, "process chemicals" (cleaning, lubrication, conductivity etc.). This functional approach will be used as a foundation for the work in this thesis, see section 2.4.

1.1.3 Emerging textile production technologies

To a great extent because of the environmental and health impacts in the textile industry, production technologies for improved environmental performance are emerging. Hasanbeigi and Price (2015) provided a review of 18 emerging technologies for energy and water efficiency and pollution reduction in the textile industry. It can be noted that many of the technologies described as emerging in the textile best reference document from 2003 (European Commission, 2003) are still on the Hasanbeigi and Price list in 2015. The development pace of these technologies has thus been slow. Other emerging technologies are described in the latest European Commission study on the Environmental Improvement of Products (IMPRO) for textiles (Beton et al., 2014), and several other emerging technologies are described in the literature (Agnhage et al., 2016; Hafrén et al., 2006; IES, 2015; Mahltig and Böttcher, 2003; Reddy et al., 2014; Terinte et al., 2014).

Table 1 lists 25 emerging technologies together with the fibre type they are applicable for and their technology development status. The list is not complete - many more emerging technologies exist. The purpose of the list in Table 1 is to show the variety in applicability of proposed emerging technologies over the textile life cycle and to different fibre types.

Figure 3 illustrates how the proposed emerging technologies are applied in different steps of textile production. The potential of these technologies to reduce the environmental impact of textile production is not obvious or to be taken for granted. Textile companies thus need guidance from environmental assessment in order to make informed decisions about whether to invest in any of these technologies.

Table 1. Proposed emerging technologies for textile production. Technologies 1-18 from Hasanbeigi and Price (2015), 19 from (Beton et al., 2014), 20 from (Agnhage et al., 2016), 21 from (Reddy et al., 2014), 22 from (Terinte et al., 2014), 23 from (IES, 2015), 24 from (Mahltig and Böttcher, 2003), and finally 25 from (Hafrén et al., 2006).

No.	Technology	Fibre type	Technology development status
1	Nanoval technology for non-wovens	Synthetic	Pilot
2	Vortex and jet spinning of yarn	Synthetic and cotton blends	Commercial with very low adoption rate
3	Friction spinning of yarn	All	
4	Multi-phase loom weaving	All	
5	Enzymatic treatments	Natural	Various commercialization stages depending on the application
6	Ultrasonic treatments	All	Pilot
7	Electron-beam treatment	Coatings and prints	Research and development
8	Ozone for bleaching cotton fabrics	Cotton	Research and development
9	Advanced cotton fibre pre-treatment to increase dye receptivity	Cotton	Pilot
10	Super-critical CO2 in dyeing	Polyester, polypropylene	Pilot
11	Electrochemical dyeing	Cellulose	Research and development
12	Ink-jet (digital) printing	All	Commercial with very low adoption rate
13	Plasma technology	All	Various stages of commercialization depending on segment
14	Foam technology in textile finishing	All	Commercial with very low adoption rate
15	Microwave energy	All	Research and development
16	Alternative textile auxiliaries	All	Various stages of commercialization depending on the type of auxiliary
17	Fuzzy logic and other expert systems	All	
18	Real-time on-line monitoring systems	All	
19	Fully fashioned knitting	All	Various stages of commercialization depending on segment
20	Bio-based coloration of polyester	Polyester	Research and development
21	Keratin as sizing agent	Synthetic and cotton blends	Research and development
22	Spun-dyed modal fibres	Regenerated cellulose fibres	Pilot
23	Spun-dyed synthetic fibres for fashion applications	Synthetic fibres	Various stages of commercialization depending on segment
24	Silica based water-repellent coating	All	Various stages of commercialization depending on segment
25	Hydrocarbon based water-repellent coating	Synthetics	Various stages of commercialization depending on segment

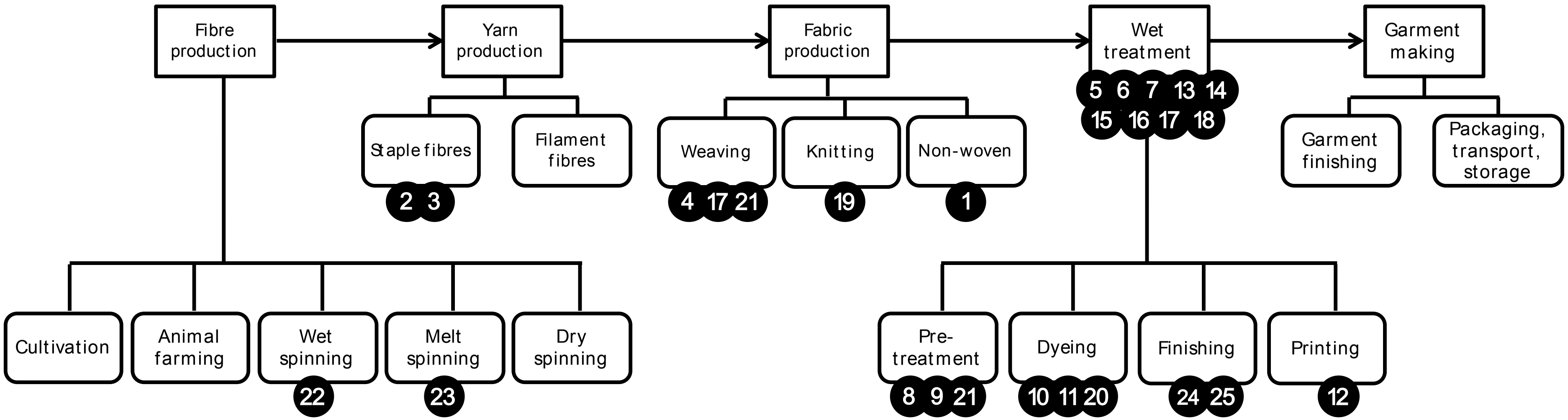

Figure 3. Application area for emerging technologies in textile production from Table 1. The main processes (rectangular boxes) of fibre production, yarn production, fabric production, wet treatment and garment making can be achieved by one or many of the underlying processes (rounded boxes). The numbers in the black circles refer to the numbering of emerging technologies in Table 1.

1.2 Environmental assessment of textile production technologies

There are many different systems in use in the textile industry for monitoring and/or improving environmental performance. Most of these are dedicated to chemical aspects and some also cover other environmental aspects, such as energy and water use. Textile companies commonly also engage with the Business Social Compliance Initiative (BSCI, 2013) or the Fair Wear Foundation (FWF, 2014) for managing social sustainability.

A broad range of ecolabels applicable to textiles exists. The Ecolabel Index currently contains a list of 108 textile ecolabels (Ecolabel Index, 2016). The globally dominating environmental ecolabel in the textile industry today is OEKO-TEX® 100 (OEKO-TEX® Association, 2013), which guarantees the absence of a pre-defined set of toxic chemicals in the textile product, verified by laboratory testing. Other common textile ecolabels are Bluesign® (BLUESIGN®, 2013) and the Global Organic Textile Standard (GOTS, 2011), both addressing the management of chemicals in the supply chain. The ecolabel approach is to guarantee that certain criteria are met, and only tells whether the products meet the criteria or not. Ecolabels thus give little guidance to the comparative performance of textile production technologies. Another commonly used tool in the textile industry is the MADE-BY Fibre Benchmark (MADE-BY, 2013), which makes a non-comprehensive inclusion of chemical issues. This benchmark bases the chemical score on the most severe 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. Such a simplified tool can therefore provide misleading conclusions with regard to the environmental performance of textile products.

Life Cycle Assessment (LCA) (ISO, 2006a), Cradle to Cradle® (C2C®) (McDonough and Braungart, 2002), and the Higg Index (SAC, 2016) are examples of tools for more holistic assessment of sustainability in the textile industry. The holistic perspective reduces the risk that the selection of a new textile production technology aimed at reducing pollution simply shifts the environmental impact from one life cycle phase to another, or from one type of environmental impact to another. In a comparison made by Bor et al. (2011), LCA was found to differ from C2C® in that it is a quantitative and holistic methodology and is independent of commercial interests. The Higg Index Facility and Brand modules and the complementary Chemicals Management Module (CMM) (Outdoor Industry Association, 2014) are primarily based on the evaluation of management routines. Thus they cannot provide the assessments of actual impact reductions and quantitative comparisons of textile production technologies that LCA can.

1.2.1 State-of-the-art in life cycle assessment in the textile sector

Life cycle assessment (LCA) is a method for quantitative evaluation of the environmental performance of products and services throughout the life cycle (Baumann and Tillman, 2004), from raw material extraction through production and use, to end-of-life, see Figure 4.

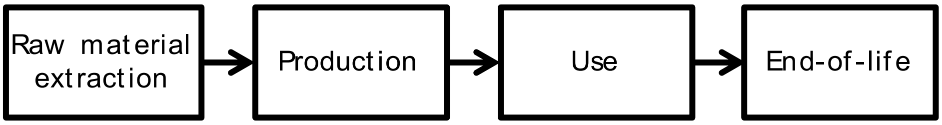

Figure 4. Generic picture of the four main life cycle phases of a product or service.

According to the ISO 14040 and 14044 standards (ISO, 2006a, 2006b), an LCA is carried out in four phases:

1) Goal and scope definition, which includes defining the system boundaries of the study and the functional unit (e.g. one day of use for a garment). This is a quantitative measure of the product's function, which in turn enables comparisons of different products.
2) Life cycle inventory analysis (LCI), where a comprehensive list of relevant inflows and outflows is developed, including emissions to air, water and soil, as well as the use of resources in the form of energy, water, material and land area, for each process included in the product's life cycle.
3) Life cycle impact assessment (LCIA), which relates the inflows and outflows from the LCI to potential environmental impacts via characterisation factors. Climate change, acidification, human toxicity, ecotoxicity, eutrophication, and resource depletion are examples of common impact categories. The selection of impact categories is made based on relevance for the study.
4) Interpretation of results, which includes drawing conclusions from the outcome of the LCI and LCIA and determining the level of confidence in the final results.

LCA is a holistic assessment method both with regard to life cycle phases and environmental impact categories, thus preventing burden shifting. The iterative character of LCA, allowing for adjustments as a result of new insights, is described by the arrows back and forth between the four phases in Figure 5. The LCA method is described in more detail in Section 2.1.

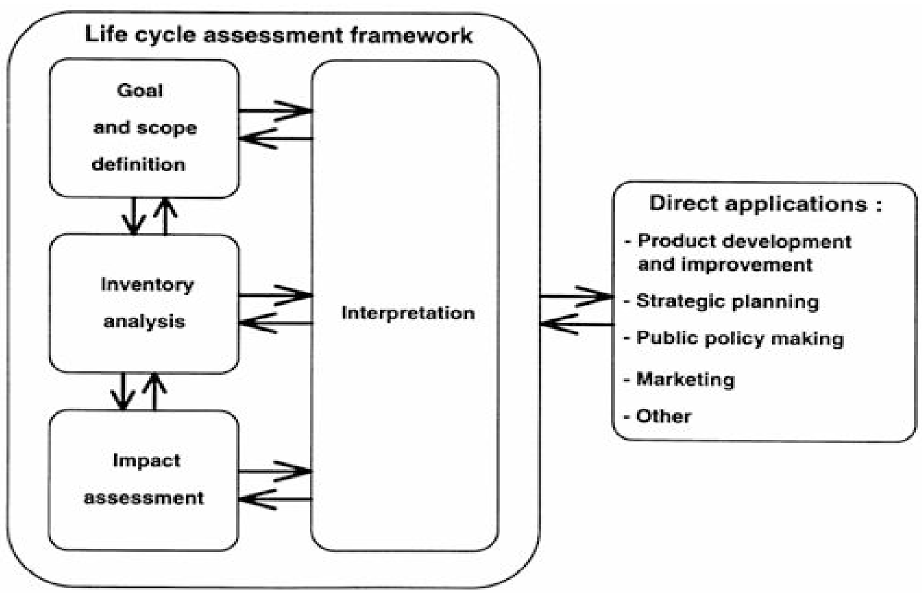

Figure 5. The four phases of an LCA and their interrelations in the LCA framework, from the International Standard ISO 14040 (ISO, 2006a).

LCA is today an important tool for comparison of environmental performance of alternative technologies that can be used to improve the Technology (T) factor of the IPAT equation (Eq. 1). LCA is used by governments, industry and academia. The European Ecodesign Directive (European Commission, 2009) as well as the European Commission initiative for Product Environmental Footprint (PEF) are based on LCA (European Commission, 2013a). One of the PEF pilots was a textile product (a t-shirt) (European Commission, 2014).

LCA would seem like an ideal tool to use for evaluating different technology solutions for producing textile products, since LCA can handle all major textile-related environmental challenges (global warming, water use and chemical pollution) in a holistic way. However, the literature study provided in Paper I shows that there are very few LCA studies of textile products compared with other product categories.

There may be several reasons underlying this situation. The large numbers of actors in the textile supply chains and the variety of materials and technologies used are generally seen as obstacles for any environmental management activities in the textile industry (Munn, 2011). A more specific reason for why LCA has been sparsely used by the textile industry might be that there are shortcomings in how toxicity impacts are handled in current practices, since chemical pollution is one of the most critical environmental aspects of textile products. In other environmental management contexts (such as legal restrictions, public procurement and environmental labelling), toxic chemicals are in fact the area where most requirements are found (Dodd et al., 2012; European Commission, 2010a, 2006; Nordic Ecolabelling, 2016; OEKO-TEX® Association, 2013). The shortcomings of both the LCI and LCIA parts of LCA in how the use and emissions of toxic chemicals is handled can thus lead to the risk of LCA giving less relevant guidance to the textile industry, or it may not become used at all.

The inventory of chemicals in LCI and the calculation of toxicity impact in LCIA are well-known to be challenging, not only for textile products (Hauschild et al., 2011). It is not uncommon in LCA studies to neglect the use and emissions of chemicals in the LCI (Sala and Goralczyk, 2013), leading to toxicity impacts from chemicals being excluded from the LCIA calculations. Furthermore, when chemicals do get included in the LCI and LCIA, the most commonly used methods for LCIA often render different toxicity scores (Owsianiak et al., 2014).

Paper I provides an overview of the state-of-the-art specifically for textile LCA studies, including toxicity impacts from chemicals. Textile chemicals were included in the LCI in only seven of the 58 published LCA studies of textile products. Moreover, of these seven studies, only four included the inventoried textile chemicals in the LCIA: Beck et al. (2000), Schulze et al. (2001), Hellweg et al. (2005) and Saouter and Hoof (2002). Beck et al. (2000) report in detail how characterisation factors for toxicity impacts have been calculated for four textile chemicals using the USES-LCA LCIA model with input data mainly from Material Safety Data Sheets (MSDS), scientific journals and extrapolation factors for uncertain data. Schulze et al. (2001) used scientific data together with EUSES default values, again for four substances calculated by USES-LCA. Hellweg et al. (2005) extended the USES-LCA model to include workplace exposure for two chemicals commonly used in dry cleaning and for which input data for physico-chemical and toxicity properties were available. Saouter and Hoof (2002) created simplified characterisation factors (CF) for the toxicity of detergents as the inverse of long term effect concentrations (CF = 1/EC50) listed in the EU Ecolabel DID (Detergents Ingredients Database) list (European Commission, 1995). The other three studies did not report any calculation of missing characterisation factors (Cotton Incorporated, 2012; Murugesh and Selvadass, 2013; Yuan et al., 2012).

This insufficient coverage of textile chemicals was identified already in 2000 by Beck et al., (2000) (one of the four articles that included LCIA of textile chemicals). Beck et al. concluded that the chemical substances included most comprehensively in LCI databases are chemicals related to energy production, since inventories for energy production have been compiled intensively. Paper I further concludes that since chemical issues are generally assessed on a qualitative rather than quantitative basis in LCA studies of textile products (51 of the 58 published studies), their comparative significance is not always comprehended.

Given that the adverse effects of chemicals are generally considered an important environmental impact of the textile industry, this sparse consideration of toxicity in environmental assessments of textile products is unfortunate. The ambition to include toxicity impacts of textile chemicals brings two interlinked challenges, which have been well described by Terinte et al. (2014). They explicitly excluded toxicity impacts in their comparative LCA study on spin-dyed fabrics versus conventional dyeing, stating that the inventory data was incomplete for textile chemicals and that there was also a lack of recommended characterisation factors for toxicity impact of the specific substances. This illustrates that in order to make comprehensive LCA studies of textile products there is a need for both method development and data collection to fill the gaps of both the LCI and LCIA.

Since the literature study in Paper I was completed there have been a few more papers published that have examined LCA of textile products or processes. The trend that many studies do not include textile chemicals in the life cycle inventory of textile products continues (Henry et al., 2015; Manda Krishna et al., 2015; Pourzahedi and Eckelman, 2015; Surdu et al., 2015). For those studies where textile chemicals are included in the life cycle inventory no additional characterisation factors for toxicity are calculated for substances where such are missing (Baydar et al., 2015; Fatarella et al., 2015; Parisi et al., 2015; van der Velden et al., 2015; Yacout et al., 2016).

Several of the studies draw the conclusion that freshwater toxicity impact for garments results primarily from fossil energy production activities, such as lignite mining waste (Fatarella et al., 2015; Manda Krishna et al., 2015; Pourzahedi and Eckelman, 2015). This might be a correct conclusion - if textile chemicals had been included it might still be the lignite extraction that dominates the freshwater toxicity, but since textile chemicals are excluded this remains unknown.

One study, Parisi et al. (2015), is explicit in that they have not calculated characterisation factors for substances missing such for toxicity impacts in their study of emerging wet treatment technologies. Parisi et al. state that "several studies discuss the data uncertainties in the characterisation factors for ecotoxicity categories, so that the evaluation of the effect of some chemical substances on soil and water emission compartments has to be treated with caution". Two studies, Manda Krishna et al. (2015) and Pourzahedi and Eckelman (2015), focus on nanosilver, and the characterisation factor coverage of this (single) substance has been checked in both studies. In the Pourzahedi and Eckelman (2015) case the USEtox characterisation factor for silver ions was combined with estimates of silver dissociation from silver nanoparticles deposited in surface waters to accurately estimate aquatic ecotoxicity resulting from nanosilver releases. However, the toxicity impact potential of nanosilver cannot be compared with the toxicity impact potential of other textile chemicals, since in these studies the latter was tacitly excluded.

1.3 Purpose and scope of research

The overarching purpose of this research has been to make possible a holistic assessment of the environmental impact of textile products using life cycle assessment (LCA). Such a holistic perspective is necessary to guide the textile industry and its stakeholders towards improved environmental performance, given the complex supply chain and a variety of environmental impacts that are described in section 1.1.

A holistic assessment implies that the most severe environmental impact categories are included. In the case of textiles these are climate change, water use and toxicity (Allwood et al., 2006; European Commission, 2003). Climate change and water use are two relatively well-developed impact categories in LCA (Hellweg and Milà i Canals, 2014). Toxicity remains challenging, however, as was briefly described in section 1.2.1 and as is described in more detail in section 2.1.4.

The specific objective of the research has therefore been to develop LCA methodology regarding toxicity impacts caused by emissions of textile chemicals, so that LCA can provide guidance in improving the environmental performance of textile products. The USEtox model (Rosenbaum et al., 2008) was selected for calculation of toxicity impacts based on the rationale that it is the LCIA method recommended by the ILCD handbook (European Commission, 2011) and was also chosen for the PEF work (European Commission, 2013b). USEtox is described in more detail in section 2.1.5. The research questions are described in section 1.3.1 and the research design in section 1.3.2.

1.3.1 Research questions

This thesis aims to answer the three research questions below. The second and third research questions were formulated based on the answer to the first research question.

Research Question 1
Does LCA provide additional knowledge regarding toxicity impacts caused by emissions of textile chemicals, compared to other less time-consuming environmental assessment methods?

The first research question investigates whether the additional effort of including toxicity impacts caused by emissions of textile chemicals in textile LCA studies can be justified. What is the additional knowledge gained from inventorying and assessing input chemicals and related emissions of substances from textile processes compared to other methods? Can the quantitative LCA approach be used in a complementary way to the existing qualitative assessment approaches for textile chemicals? Can the use of simplified methods for toxicity assessment substitute the time-consuming work of developing characterisation factors for the toxicity impact of textile chemicals for the LCIA?

Paper I investigates the current state-of-the-art of how toxicity impacts from textile production processes are handled in textile LCA studies. In Paper I it is identified that, in practice, LCA studies of textile products rarely include emissions of textile chemicals in the LCI. In the few cases where these have been included in the LCI, the LCIA in general has excluded emissions of textile-related substances. Paper I also describes an explorative LCA case study where the order of magnitude of toxicity impacts caused by emissions of textile chemicals was examined. The latter were found to be in the same order of magnitude as the toxicity impacts from other sources in the life cycle, such as cotton cultivation and emissions from the combustion of fuels, hence motivating further development of LCA to include textile chemicals.

Paper II investigates whether the results from toxicity impact assessment with the USEtox LCIA method differs from those resulting from two simplified environmental assessment methods, and concludes that the simplified methods cannot substitute USEtox. Paper II further identifies a gap regarding the existence of characterisation factors for textile-related substances in the LCIA.

Research Question 2
Which LCA data gaps are the most important to fill in order to cover the most common processes and chemicals in the textile industry?

The second research question addresses the challenge of filling the LCA data gaps in a systematic way, both for LCI and LCIA data. The variety of textile processes (>100 different processes) and textile chemicals (>15,000 different chemicals) currently in use makes the LCA data gaps impossible to fill entirely. Instead a prioritization of the most critical gaps to fill with regard to textile processes and textile chemicals is needed.

Paper III explores the possibility of investigating textile products at a higher system level. The basis for the prioritization of which LCA data gaps to fill is generated by lifting the textile LCA perspective from the garment level to the industry sector level, thus considering the total yearly consumption of clothes in a whole country, in this case Sweden. At the industry sector level it was possible to identify the most commonly occurring textile processes and systematically develop representative LCI data for them.

Research Question 3
How can methodology be developed to fill the prioritized LCA data gaps from research question two with a reasonable demand on time and competence?

Research question three is formulated from the aim of advancing the field of LCA of textile products to include textile chemicals. Most LCA practitioners have limited time and education in chemistry and would need ready-to-use data to handle chemicals and their related toxicity. However, even if the prioritized LCA data gaps from research question two were to be filled, there will always be data gaps; the next LCA study might be assessing a technology or chemical outside the coverage, data will age, etc. So in addition to filling current data gaps through case studies, it is important to develop methods for how to collect data, which is reported in Paper IV and V, based on the experiences from previous case studies.

Papers IV and V provide ready-to-use characterisation factors and LCI data, respectively, but more importantly they also present the methodology developed in the case studies for deriving data. Paper IV provides a methodology for selection of toxicity data for increased transparency and reduced uncertainty and presents calculated USEtox characterisation factors for a set of textile chemicals for which characterisation factors were previously missing. Paper V provides a generalised framework which has also been filled with LCI data sets for a number of common textile production processes. Further the nomenclature developed for the categorisation of textile processes and textile chemicals is presented in order to facilitate future LCI data acquisition. Paper V also demonstrates the usefulness of the developed methodology in two illustrative examples. Together, Papers IV and V thus constitute a parallel development of LCI and LCIA methodologies.

1.3.2 Research design

The research design has been constructed to fit the objective of advancing the LCA of textile products in the field of emissions of toxic substances from textile chemicals and to answer the three research questions, see Figure 6. The results from Paper I were split into two focus areas, LCI and LCIA, which were then developed in parallel to achieve the match between LCI and LCIA coverage. The specific research methods used to answer the research questions are described in Chapter 2.

Objective:
Advancing life cycle assessment (LCA) of textile products focused on textile chemicals

↓

RQ 1:
Does LCA provide additional knowledge regarding toxicity impacts caused by emissions of textile chemicals, compared to other less time-consuming environmental assessment methods?

↓

RQ 2:
Which LCA data gaps are the most important to fill in order to cover the most common processes and chemicals in the textile industry?

↓

RQ 3:
How can methodology be developed to fill the prioritized LCA data gaps from research question two with a reasonable demand of time and competence?

↓

Result:
Advancing life cycle assessment of textile products to include textile chemicals (LCI + LCIA)

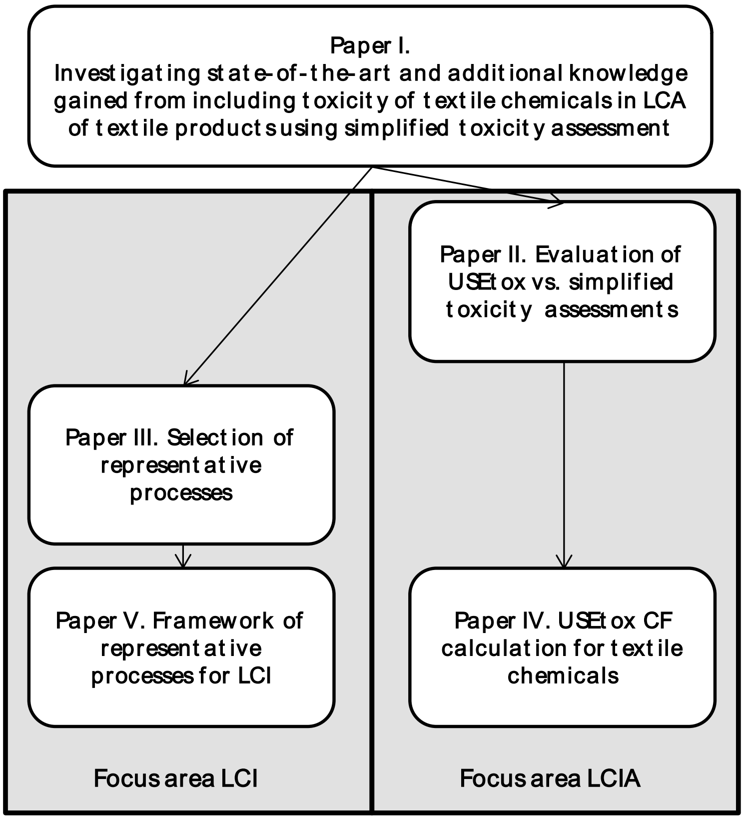

Figure 6. Research design.

2 Research methods

The research methods can be classified according to three general approaches, depending on the perspective that the researcher adopts to the method; induction, deduction, or abduction (Bryman and Bell, 2011). In the deductive research process the starting point is a hypothesis that is tested empirically (for example if it applies to specific circumstances). The theoretical statements are thus confirmed by empirical testing (Little, 1991). The opposite perspective is the inductive research process, where empirical observation is the starting point for theory building. The term abductive research also exists, in which the gap is bridged between empirics and theory for cause-effect relations but in this case the premises do not guarantee the conclusion (i.e. there may be alternative explanations to the observed effect). In most research processes all three perspectives are used in different phases of the research (Bryman and Bell, 2011).

LCA as defined by the ISO 14040 standard (ISO, 2006a) is the methodological framework within which this thesis has been written, and is described in more detail in section 2.1. LCA is a systems analysis method (Baumann and Tillman, 2004), and in this field method development is commonly based on empirical experiences from case studies (inductive or abductive perspective) (Miser and Quade, 1985). Dubois and Gadde (2002) have described the abductive logic-based systematic combining approach as particularly useful for the development of new theories, letting methodological framework, empirical fieldwork, and case analysis evolve simultaneously in case studies where the boundaries between phenomenon and context are not clearly evident. As systems analysis methods are difficult to validate, case studies can be used to provide proofs of concept (or calls for adjustments) of the developed method and theory (Miser and Quade, 1988).

The objective of the research has been to advance LCA of textile products regarding toxicity impacts from textile chemicals so that LCA can be used to provide guidance to the actors and stakeholders of the textile industry in their work towards improved environmental performance. The research process has involved three LCA case studies, described in section 2.2. The case studies served as empirical context for the development of the framework for categorisation and inclusion of textile processes and textile chemicals in LCA studies, and have alternated between empirical work and method development, as illustrated in Figure 7.

The following sections (2.1-2.4) describe the methods used to answer the three research questions defined in section 1.3.1.

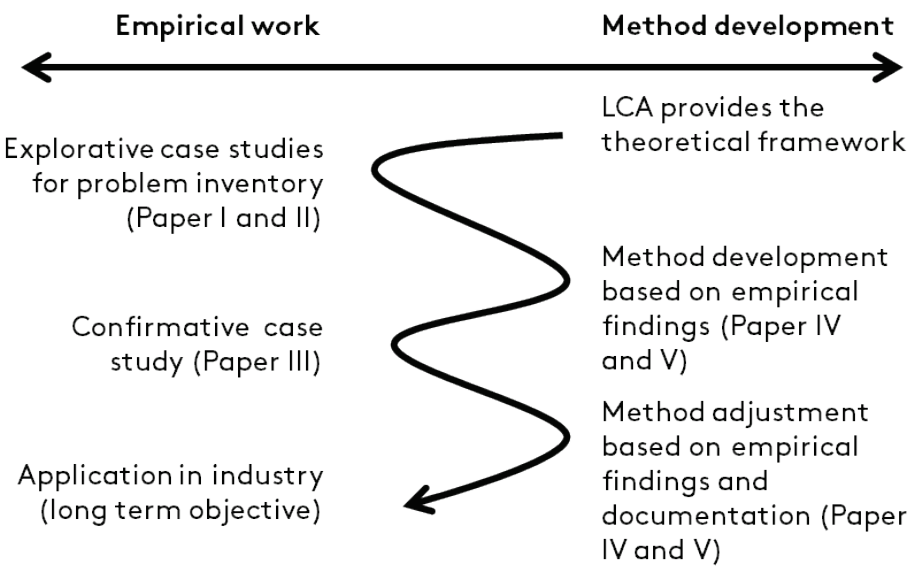

Figure 7. Research process, alternating between empirical work and method development in different phases of the research.

2.1 Life cycle assessment (LCA)

LCA was briefly described in section 1.2. It was mentioned that the entire life cycle, from raw material extraction through production, use, to end-of-life is generally included (Figure 4) and that LCA is carried out as an iterative process of goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation of results (Figure 5) according to the ISO standards (ISO, 2006a, 2006b). This section will go a bit deeper into the method and work process of LCI and LCIA, and will explain how the work in this thesis has been performed. There are also several textbooks and handbooks about LCA with detailed descriptions of methodological issues, in addition to the ISO standards (Baumann and Tillman, 2004; European Commission, 2010b; Jeroen B. Guinée et al., 2002; Klöpffer and Curran, 2014), and in Europe, the PEF guidelines are commonly used as a guidelines (European Commission, 2013a).

Figure 8 provides an overview of how LCA is carried out in practice and the components of the LCA work. The LCA practitioner creates a model of the product life cycle. The LCI model depicts emissions to air, water and soil, as well as the use of resources in the form of energy, water, material (including chemicals) and land area for each process included in the product's life cycle. The LCI model can be constructed with data from specific processes inventoried for the study or with generic data from LCI databases that contain ready-made LCI data for a variety of processes. The LCIA model depicts the potential environmental impacts that resource use and emissions can cause. The LCIA model can be constructed using a ready-made LCIA package that contains LCIA data for a variety of emissions and resources. The LCIA model can also be constructed with specific impact data inventoried from the study using an impact assessment method to construct new characterisation factors, although this is very rare. The LCA practitioner constructs and applies suitable LCI and LCIA models to fit the goal of the study. The product's life cycle impact is then calculated from the LCI and the LCIA data. Usually LCA software is used, as these models contain large data sets. The LCI and LCIA databases are often routinely complemented with new data generated from a study (dotted lines in Figure 8).

When using LCA for environmental assessments, the limitations of the method should also be known. LCA exclusively assesses impacts that are caused by physical inflows and outflows between the analysed system and the ecosphere that occur during normal and abnormal operating conditions of the included processes, but excluding accidents, spills, and the like (European Commission, 2010b). The environmental aspects that cannot be quantified are often excluded, although they can be described qualitatively in the LCA report. Furthermore, LCA is known to have limitations in how to model both temporal and geographical variations (Hellweg and Milà i Canals, 2014).

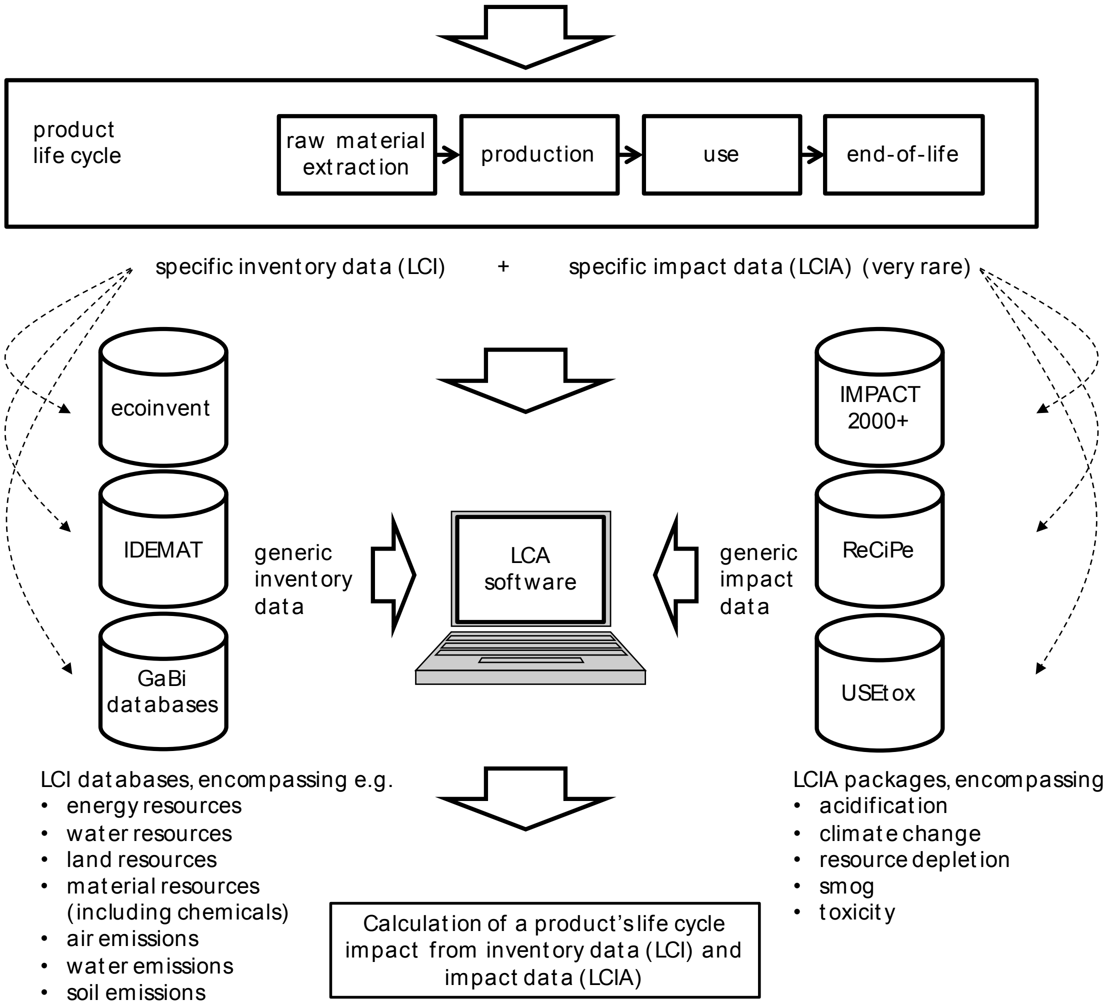

Figure 8. Components of the LCA work. The calculation of the product's life cycle impact is usually made using software. LCI databases (to the left) and LCIA packages (to the right) are in most cases used to model the product life cycle and its environmental impact.

2.1.1 Goal and scope definition

The goal definition is decisive for all the other phases of the LCA. It guides all the detailed aspects of the scope definition, which in turn sets the frame for the LCI work and LCIA work. The decision-context determines the most appropriate approach to be applied for the LCI modelling framework (attributional or consequential) and related issues, such as the allocation approach (allocation or system expansion). For descriptions of these approaches the reader is referred to the handbook created for the International Reference Life Cycle Data System

(ILCD) (European Commission, 2010b). Another important decision in the scope phase is the selection of impact categories for the LCIA.

The overall goal for the research presented in this thesis has been to use LCA to assess and to be able to differentiate between the environmental impacts of different textile processes, including emerging technologies. Since the aim has been to understand the relative significance of different textile processes and textile chemicals currently in use, the attributional LCA approach has been used consistently throughout the three case studies.

The scope of the thesis work has been determined by the research context. Since the research has been mainly conducted within two projects, Mistra Future Fashion (Mistra Future Fashion c/o SP, 2016) and SUPFES (SUPFES c/o Swerea, 2015), the scope has been limited to textile garments, excluding home textiles and other types of non-garment textiles. For the case studies the choices of impact categories and characterisation methods vary and are further described in section 2.2.

2.1.2 Life cycle inventory analysis

The life cycle inventory analysis (LCI) phase of an LCA generally requires the highest efforts and resources with regard to data collection and modelling (European Commission, 2010b). Several different approaches to LCI modelling can be adopted, of which constructing a process flow model is the most common (Suh and Huppes, 2005). As Figure 8 shows, a model of the product life cycle is created, usually based on a mixture of data specifically inventoried for the study and generic data from LCI databases and literature.

Figure 9 shows schematically how each modelled step in the textile life cycle (in this case a bleaching step) consists of foreground processes and background processes. The foreground processes are those for which measures may be taken as a result of decisions based on the study. The background processes are influenced by measures taken in the foreground system, but their mode of operation is not investigated in the study in question as exchange with the foreground processes takes place, for example, through a market (Tillman, 2000).

In the three case studies presented in this thesis, data search included searching in generic data sources for available data. Commercial and/or open-access LCI databases, such as ecoinvent, the GaBi database, IDEMAT and ELCD, and the literature were explored. However, textile process LCI data including textile chemicals was found to be scarce. Most of the foreground process data was therefore specifically inventoried for the study. The background process data has deliberately been selected to be generic, so that variations in environmental performance are mainly due to differences in the foreground processes and not the background processes.

The goal of the thesis work has two main implications for the data collection. Firstly, the target textile processes for data collection are processes that have a high degree of representativeness, meaning that they are commonly occurring processes and are plausibly used for many textile products. Secondly, in Papers III and V the potential reduction in environmental impact with emerging textile production technologies is assessed, therefore the models of current processes were chosen to represent quite modern technology. For that reason Best Available Technology (BAT) or close to BAT processes were targeted. If technology that is known to be outdated and will be replaced within the next few years would be modelled, the answer to what interventions are needed would probably be to change to BAT, which is likely to happen in any case. However, the choice of BAT means that the environmental impact of textile production will be slightly underestimated.

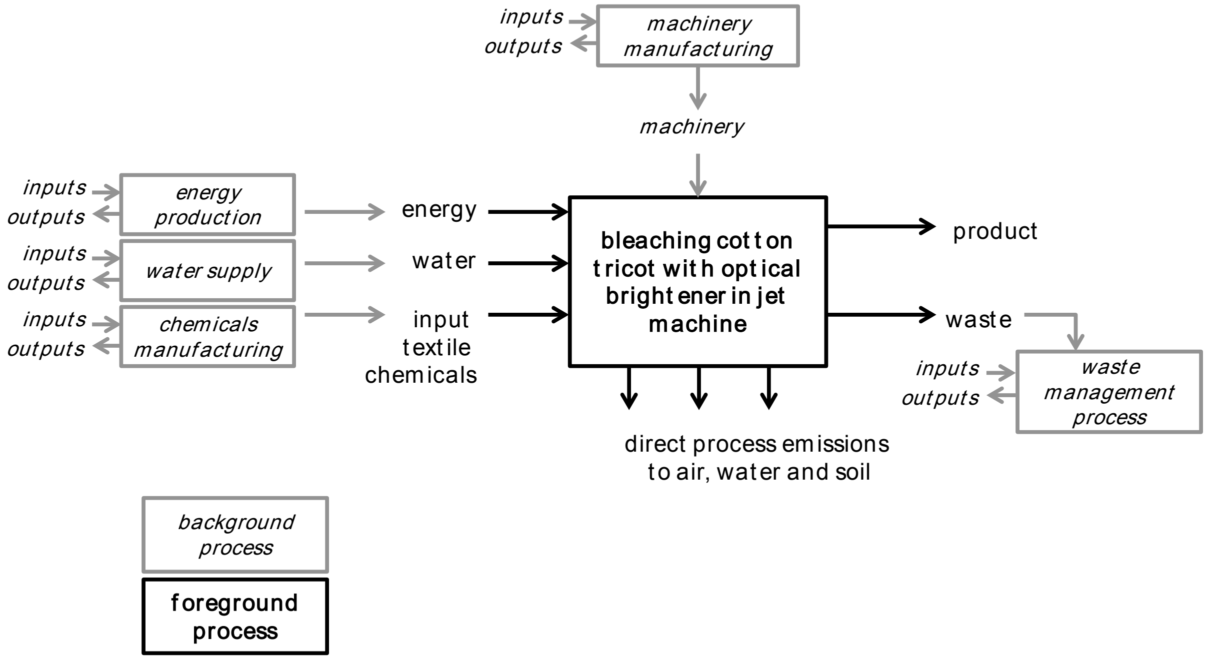

Figure 9. Illustration of background processes and foreground processes. Each modelled process (in this case a bleaching process) in the textile life cycle consists of a foreground process, for which measures may be taken as a result of decisions based on the study. For the foreground processes, specific data about inputs and outputs have been collected. For background processes, generic data from databases have been mostly used.

2.1.3 Life cycle impact assessment

In the life cycle impact assessment (LCIA) phase, inflows and outflows from the LCI are translated into indicators for a variety of impact categories that reflect potential environment and health impacts, as well as resource scarcity impacts (Hauschild and Huijbregts, 2015). This calculation is based on characterisation factors (CF) under impact category *j* for elementary flow *i,* which represent the predicted contribution to an Impact Score (IS) per quantity emission or resource consumption (Q):

$$IS = \sum_{i,j} Q_i \times CF_{i,j} \qquad \text{(Eq. 2)}$$

The characterisation factors are generally calculated using models for environmental fate, impact pathways and cause-effect relations. Since the early 1990s numerous LCIA models have been developed, and collections of models covering a range of impact categories have also been assembled into LCIA packages. The most commonly used LCIA models are described in the ILCD handbook on LCIA, which also provides recommendations on which models to use (European Commission, 2011). The ILCD recommendations thus form an additional LCIA package consisting of the IPCC (Intergovernmental Panel on Climate Change) list of characterisation factors for the impact category climate change, the USEtox database of characterisation factors for toxicity impacts etc. It is important to note that LCA and the impact assessment analyses the potential environmental impacts, rather than making predictions of actual environmental impacts. LCA studies usually aim for best-estimates in the modelling of all impacts, meaning that precautionary assumptions and conservative estimates are typically avoided (Hauschild and Huijbregts, 2015).

The assessment of potential impacts is performed at midpoint and/or endpoint level going down the impact pathway. Both levels have advantages and disadvantages. In general, at midpoint level the results are reported close to the lowest aggregated place where a common mechanism for a variety of environmental aspects exists, and for a set of impact categories. The results are more accurate and precise compared to endpoint level, but leave the reader to assess the significance of each impact category. The following midpoint impact categories are covered by the ILCD handbook on LCIA (European Commission, 2011): Acidification (land and water), Climate change, Ecotoxicity, Eutrophication (land and water), Human toxicity, Ionizing radiation, Land use, (Stratospheric) Ozone depletion, (Ground-level) Photochemical ozone formation, Resource depletion (minerals, fossil and renewable energy resources, water) and Respiratory inorganics. Endpoint level results are generally delivered as impact on three Areas of Protection. These are: Human health, Natural environment and Natural resources (European Commission, 2011). A third opportunity for impact assessment is to perform a weighting step (ISO, 2006a). In this step the Areas of Protection are given a relative significance and the results of the potential impacts are aggregated to a single score. Weighting has not been considered in this thesis.

For the case studies in this thesis the choices of impact categories and characterisation methods vary and are described in section 2.2. As stated in the introduction, climate change, water use and toxicity are the major environmental impacts from the textile industry. Global warming potential (GWP) is routinely used to assess impacts on climate change in LCA, and exists in several slightly different variants (Goedkoop et al., 2008; J.B. Guinée et al., 2002; IPCC, 2013). Water use can be assessed using the water scarcity approach (Frischknecht et al., 2008), which is the method recommended by the ILCD handbook (European Commission, 2011). In addition, several other indicators of life cycle water use can be applied to assess the environmental burden of water use (Boulay et al., 2015; Hagman et al., 2013; Hoekstra et al., 2011). The LCIA models for potential toxicity impacts, and the simplified methods for toxicity assessment used, are described in section 2.1.4.

2.1.4 Toxicity impact assessment in LCA

The toxicity impact assessment is the main focus of this thesis. Different toxicity impact assessment models are available to the LCA practitioner. The ILCD recommended practice is to use the USEtox model (Rosenbaum et al., 2008). ReCiPe is another commonly used LCIA package that incorporates the USES-LCA model for toxicity impacts (Goedkoop et al., 2008). A third commonly used LCIA package is IMPACT 2002+ that uses the IMPACT 2002 toxicity model (Jolliet et al., 2003). The scope of, and the assumptions behind, these models are somewhat different and they have been shown to not generate consistent results for toxicity impacts (Mattila et al., 2011; Owsianiak et al., 2014).

Hauschild et al. (2011) summarizes the challenges of models for characterization of toxic impacts from chemical emissions. The UNEP–SETAC Life Cycle Initiative leading to the development of USEtox aimed at solving the problem with multiple models that disagree in modelling principles and in the characterization factors they provide, at the same time as each of them only cover a small fraction of the number of chemicals that are applied in products (Sala et al., 2012). Still, a lot of criticism of USEtox (as well as the other toxicity impact assessment models) exists. Although the coverage of the USEtox database is now extended to over 3,000 chemicals, there are still many more chemicals that need to be modelled for LCA purposes (Birkved and Heijungs, 2011). The fate, exposure and toxic effect characteristics of several substances, such as metals, inorganic chemicals, organometallic and amphiphilic chemicals, continues to be problematic for the USEtox model (Dong et al., 2014). The spatial resolution in models of the chemical emissions, and resulting toxicity impacts, is also a major challenge (Sala et al., 2011).

The development of the ILCD system led to the insight 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). As the development of characterisation factors is resource demanding, previous studies have used a range of methodologies for simplified incorporation of toxicity in LCIA. A common approach to a simplified assessment has been to merge the life cycle perspective with chemical risk information to deal with the problem of missing characterisation factors for toxicity impacts (Askham, 2011; Finnveden et al., 2009; Laurent et al., 2012; Liu et al., 2012; Scheringer, 1999). In such case the risk assessment is included in a project as an add-on study, and can thus be considered in the interpretation phase.

2.1.5 Toxicity impact assessment models used in the current research

The USEtox database (ready-made characterisation factors for over 3,000 substances) and model(for environmental fate, impact pathways and cause-effect relations with which the practitioner can calculate new characterisation factors) (Hauschild et al., 2008; Rosenbaum et al., 2008) were selected as the toxicity impact assessment method for the research presented in this thesis. The rationale for selecting USEtox is that it is the method recommended by the ILCD handbook on LCIA (European Commission, 2011), it is the chosen method for the PEF (European Commission, 2014) and it has been used by both academic and industry LCA experts in a number of published studies. USEtox contains a global, nested, multi-media 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 (Hauschild et al., 2008). In USEtox, a human toxicity characterization factor for a substance is derived from the product of three matrices, including fate factors (FF), human exposure factors (XF), and human toxicological effect factors (EF):

$$CF = EF \times XF \times FF \qquad \text{(Eq. 3)}$$

An ecotoxicological characterization factor for freshwater ecosystems for a substance is likewise derived from the product of fate factors (FF), freshwater ecosystem exposure factors (XF), and freshwater aquatic ecosystem toxicity effect factors (EF) (Huijbregts et al., 2015b).

In Paper II two simplified methods for toxicity assessment were used to benchmark the USEtox model; the Score System (Laursen et al., 2002) and the Strategy Tool (Askham et al., 2012).

The Score System was developed in the 1990s by the Federation of Danish Textile and Clothing in Denmark (Laursen et al., 2002). It is a semi-quantitative method for aggregating factors describing the intrinsic properties of chemicals and the scale of their use in a process. The method was integrated into the waste water permit approval process of Ringkøbing County in Denmark. It was selected on the basis that it is presented as a viable method in the Integrated Pollution Prevention and Control (IPPC) Reference Document on Best Available Techniques for the Textiles Industry (European Commission, 2003), and has also been used as a simplified ecotoxicity assessment method in previous LCA studies and guidelines for the textile industry (Krozer et al., 2011; Sweden Textile Water Initiative, 2016).

According to the Score System each substance is given a score from 1 p (point) to 4 p for each of four criteria (A-D):

- A - amount of substance discharged weekly (1 p = < 1 kg/week), 4 p = > 100 kg/week),
- B - biodegradability (1 p = > 60% BOD[2], 4 p = BOD/COD[3] ratio ≤ 0.5),
- C - bioconcentration factor (BCF) (1 p = BCF < 100, and 4 p = BCF ≥ 100), and
- D - toxicity, measured as effect concentration (EC) divided by effluent concentration (1 p = > 1000, 4 p = < 10)

The four scores are then multiplied together so that the lowest possible value is 1 (best environmental performance) and the highest possible value is 256 (worst environmental performance). Missing information invokes the highest score, i.e. in the case of data missing for a property the value of 4 should be given to the substance for that property. For detailed LCA results of the case study, the reader is referred to Roos and Posner (2011).

The Strategy Tool for assessment of human toxicity and ecotoxicity impacts was developed by Askham et al (2012). The Strategy Tool is a semi-quantitative method developed to assist a paint production company making strategic decisions in product development. The Strategy Tool evaluates the chemical content of products in a simplified way, based on the available information in the safety data sheet (SDS). This method was selected because it uses input data that is readily available for most chemical products and is thus a user-friendly method also for LCA practitioners who are not experts in chemistry. This user-friendliness provides considerable potential for the tool to be used correctly, as was further explored in Paper II. A translation to today’s hazard phrases according to the Classification, Labelling and Packaging of substances and mixtures (CLP) regulation (EC) No 1272/2008 (European Commission, 2008) was made for the purpose of the study, see Table 2.

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[2] Biochemical Oxygen Demand
[3] Chemical Oxygen Demand

Table 2. The division of risk phrases in the Strategy Tool from Askham et al. (2011) translated into today's hazard phrases according to the CLP regulation (European Commission, 2008) (Table S.3 from Paper II). Phrases starting with H3 are health related and phrases starting with H4 are environmentally related.

Hazard level	Strategy Tool model	Hazard phrases
Low = score 1	R20	H332
	R20/21	H332, H312
	R20/21/22	H332, H312, H302
	R20/22	H332, H302
	R21	H312
	R21/22	H312, H302
	R22	H302
	R36	H319
	R36/38	H319, H315
	R38	H315
	R50	H400
	R53	H413
Medium = score 3	R23	H331
	R23/24	H331, H311
	R23/24/25	H331, H311, H301
	R23/25	H331, H301
	R24	H311
	R24/25	H311, H301
	R25	H301
	R34	H314
	R35	H314
	R36/37	H314, H335
	R36/37/38	H314, H335, H315
	R37	H335
	R37/38	H335, H315
	R41	H318
	R43 (moderate)	H317
	R48/20	H373
	R48/21	H373
	R48/22	H373
	R51/53	H411
	R52/53	H412
High = score 10	R26	H330
	R27	H310
	R28	H300
	R40	H351
	R42	H334
	R42/43	H334, H317
	R45	H350
	R46	H340
	R48/23	H372
	R48/24	H372
	R48/25	H372
	R49	H350i
	R60	H360F
	R61	H360D
	R62	H361f
	R63	H361d
	R64	H363
	R68	H341
	R50/53[1]	H400, H410
	R53	H410

[1] In Askham et al. (2011), this risk phrase is allocated both to categories, Low and High. As R50/53 is the indication of a possible PBT (persistent, bioaccumulative and toxic) substance, this has only been placed here in the High category after discussion with the author.

2.1.6 Interpretation of results

The interpretation phase of the LCA study is where the questions posed in the goal definition are answered. Interpretation of results includes drawing conclusions from the outcome of the LCI and LCIA and determining the level of confidence in the final results (European Commission, 2010b).

One of the elements of the interpretation phase is the completeness check (European Commission, 2010b). Regarding toxicity assessment in LCA studies of textile products, it should be acknowledged that life cycle toxic emissions reported in many inventories and processes from a database such as ecoinvent are often mostly correlated to energy (Beck et al., 2000). This could be expected for emissions that are related to combustion processes, which are well covered by databases such as ecoinvent (Hauschild and Huijbregts, 2015).

A second important component of the interpretation phase is the sensitivity analysis. The environmental issues that are found to be significant for the final result and conclusions of the study are evaluated to ensure consistent handling throughout the study, in line with the goal and scope. Scenario analysis and uncertainty calculations are the quantitative methods used to support this (European Commission, 2010b). Both methods have been used in the case studies to increase the understanding of the reliability of the final results.

2.2 LCA case studies

The three different case studies conducted within the scope of this thesis are described below.

2.2.1 Case study 1: Assessing the comparative significance of textile chemicals

Research question one was examined in a project commissioned by Stockholm County Council, and described in Paper I. It was set up as an explorative case study for assessing the comparative significance of textile chemicals in the life cycle of hospital garments. LCI data for foreground processes were collected from suppliers, and ecoinvent data was used for background processes (Ecoinvent, 2010). The Stockholm County Council's goal with the project was partly to quantify the environmental gain from using unbleached garments compared to bleached garments via a comparison of white hospital nightgowns. An additional goal was to identify the most environmentally benign dyestuff via a comparison of blue cardigans. Two types of hospital garments were therefore studied; a white, 337 gram night gown for patients, and a blue, 496 gram cardigan for hospital staff. Both garments were knitted, constructed of cotton/polyester blends and manufactured in Tirupur, southern India. In the use phase the garments were assumed to be washed in an industrial laundry, and considered to be used for the whole technical lifespan, i.e. until the fabric or the stitching is worn out. Impacts of use phase processes (washing, drying and distribution) and disposal were identical for both garment types.

In Case study 1, environmental performance was expressed as global warming potential (GWP), ecotoxicity and human toxicity. The GWP was calculated with ReCiPe, Midpoint (H) V1.06/World ReCiPe H (Goedkoop et al., 2008) and the toxicity was calculated with USEtox (Rosenbaum et al., 2008) (existing characterisation factors).

The coverage of textile chemicals in the USEtox database was discovered to be too low to answer the research question or to meet the goal of Stockholm County Council. The time limitations of the study denied the possibilities to calculate characterization factors using the USEtox model. A simpler method, the Score System (Laursen et al., 2002), was therefore used as a supporting assessment method to calculate the potential ecotoxicity impact from textile chemicals.

2.2.2 Case study 2: Comparing toxicity assessment methods

Based on the data gap in Case study one in Paper I, resulting from the inability to evaluate the toxicity impacts of textile chemicals with USEtox, Paper II investigated whether the results from toxicity impact assessment with USEtox differed from those resulting from two simplified environmental assessment methods. This was done in order to answer research question one.

Thus for Paper II another explorative case study was set up, this time within the Mistra Future Fashion project (Mistra Future Fashion, 2014). It was a gate-to-gate LCI of the wet treatment of a white cotton t-shirt processed in a jet dyeing machine. The inventory results for use and emissions of textile wet treatment chemicals were then extracted and evaluated with three different quantitative or semi-quantitative LCIA methods for toxicity footprints; USEtox (Rosenbaum et al., 2008) (existing and additional characterisation factors), the Score System (Laursen et al., 2002), and the Strategy Tool (Askham et al., 2012).

2.2.3 Case study 3: Identifying critical LCA data gaps

Research question two aimed to identify the most critical LCA data gaps to fill in order to cover the most common processes and chemicals in the textile industry. Research question three addresses the challenge of filling the LCA data gaps in a systematic way. Case study three tested two hypotheses:

- whether the most critical LCA data gaps to fill regarding textile processes and textile chemicals can be found via performing LCA on sector level instead of garment level (to answer research question two), and
- whether data collection can be aided by an exclusive and user-oriented nomenclature (to answer research question three). Exclusive means here that the set nomenclature cannot be extended with any new values (entries), while inclusive implies that this is possible (Erlandsson et al., 2006).

Case study 3 was conducted on an industry sector level (the yearly consumption of clothes in Sweden) and is described in detail in Paper III, as well as in Roos et al. (2015). The scope was decided using the statistics on import, export and domestic production from the Swedish statistics for 2012 (Statistics Sweden, 2014). These statistics are based on 34 groups of garments, see Appendix 1. As shown in Appendix 1, the 34 groups of garments were represented by models of five archetype garments; a T-shirt, a pair of jeans, a dress, a jacket, and a hospital uniform. These five garments were modelled to provide a simplified but representative picture of Swedish annual consumption of clothes in terms of material content, fabric construction, finishing, consumer behaviour and end-of-life handling.

In Case study 3 the selection of impact categories was based on the recommendations in the ILCD handbook (European Commission, 2010b), as this represented the most current consensus in the European LCA community at the beginning of the research process. Some impact categories recommended by ILCD were omitted as they were deemed to be of low relevance for the textile industry (e.g. ozone layer depletion and ionising radiation), and some impact categories missing in the ILCD recommendations were added, as they were considered highly relevant for the textile industry (e.g. agricultural land occupation).

The identification of the most important textile processes to include in the LCI was based on two criteria: 1) frequency of occurrence of the technologies in order to cover as large a share of the clothing industry as possible and 2) the ability to capture the variation in environmental performance between technologies. Knowledge about the occurrence of technologies was gained from searching the literature, site visits and industry dialogue about the current technologies in use. Knowledge about the variance in the environmental performance was a result from the calculations made in the third case study. Based on above, the framework was filled with 30 LCI data sets for textile production processes.

Paper V provides two illustrative examples on how the framework and the LCI data sets can be used. The first example is a calculation of potential toxicity impacts from the total yearly Swedish clothing consumption. Paper III provides results for carbon footprint and scarcity-weighted water use and Paper V adds results for freshwater ecotoxicity impacts. The inventories were created by combining the developed LCI data sets to give a representative picture of the garments produced for the Swedish market in terms of materials and fabric constructions.

The second example is a calculation of the effectiveness of different interventions for reducing the environmental impacts. Ten different interventions were investigated. The inventories were created from varying the selection of LCI data sets from the first example and combining them to describe the different scenarios. In the case of collaborative consumption via for instance clothing libraries (interventions 1 and 2), the service lives of garments are prolonged while the number of garments at the consumer's disposal is not reduced (an ad hoc assumption was made that 40% of the total consumed garments double their service life). Offline means that the consumers transport themselves to and from a physical store or library, while in the online case the consumers receive the garments via a delivery service. There are further three scenarios with material level recycling of polyester and cotton (the assumptions here are that for intervention 3, all polyester is replaced, for intervention 4, all cotton is replaced with a cotton mix of 15% mechanically recycled content, and for intervention 5, that all cotton is replaced with chemically recycled cotton (lyocell). Intervention 6 assumes that all cotton is replaced with forest based lyocell. Regarding intervention 7, it should be noted that increased service life here implies a reduction of money spent on apparel consumption (in contrast to the collaborative consumption scenarios, interventions 1 and 2) and that the financial savings associated with this intervention can give rise to more complex outcomes including so-called rebound effects. Interventions 8-10 assumes in turns that renewable energy is used throughout the life cycle of garments, the energy use in the garment production phase is 20% more efficient and the consumers go by foot or on bike to the store. The different interventions are more thoroughly described in Paper III where also results for carbon footprint and water use are reported.

2.3 Literature review

Literature review has been an important method used to answer especially research question one. From the experiences shared in the academic literature, as well as in the grey (non-academic) literature, a comprehensive picture of state-of-the-art regarding inclusion of emissions of toxic substances in LCA studies of textile products was created.

The Scopus, SciFinder and ProQuest databases were used for academic literature. The search phrases for Scopus and ProQuest are listed in Table 3 (taken from (Roos, 2015)). No limitation regarding temporal coverage was applied. For SciFinder the search phrase "life cycle assessment of textile" was used. Google was used as the search tool for grey literature mining. Reference and citation search was also performed for the publications that were relevant, in a forward and backward snowballing manner (Wohlin, 2014). To enhance the comprehensiveness the results were sorted on the basis of the textile life cycle phase (see Figure 4) and the fibre material, in order to make potential gaps visible. The results can be seen in Table 1 of Paper I.

To answer research question two another type of documents was studied. Statistics on import, export and the production of clothes (Statistics Sweden, 2014) have been an important source for identification of the most important textile production processes, and hence the most important textile chemicals to fill the data gaps for. For creating the LCI methodology (research question three) textile industry guidelines were used, such as the reference document on best available techniques (BAT) for the textiles industry (European Commission, 2003) and the TEGEWA (Verband der TExtilhilfsmittel-, GErbstoffe-, und WAschrohstoffe-Industrien e.V.) international textile auxiliaries buyer's guide (TEGEWA, 2008).

Table 3. Search phrases for the literature search in Scopus and ProQuest.

Search phrase	Number of hits
(TITLE-ABS-KEY[1] (textile* AND chemical*) AND SRCTITLE[2] (life cycle assessment))	6
(KEY[3] (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

[1] The search phrase TITLE-ABS-KEY commands search in title, abstract and keywords.
[2] The search phrase SRCTITLE commands search in the source title (the journal's title).
[3] 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.

2.4 Nomenclature development

Research question three addresses the challenge of filling the LCA data gaps in a systematic way. The nomenclature development fundament is the need of consistent handling of data in an LCA study. The LCA practitioner enters the textile technology field as an external actor, aiming at assessing a textile production chain which is very diverse in materials, processes and equipment. Both natural and synthetic raw materials are used and the variety of processes is also large; agricultural, chemical and mechanical processes are all included. None of the actors along the production chain possess a complete overview of the input materials, processes and equipment used in the other steps. The terminology used is different for each of the many steps in the production, and for each of the input materials (fibres, input chemicals, auxiliaries). Communication between the actors in the long supply chain (see Figure 1) is also often hindered by linguistic and cultural differences. The challenge of putting together a complete LCI (including textile chemicals) for textiles is immense for any LCA practitioner.

Furthermore, the compilation of the inventory of input and emitted chemicals is particularly difficult for an LCA practitioner who is not skilled in chemistry. Chemistry expertise is needed to handle firstly the nomenclature of chemical substances since there are several different nomenclatures in use (CAS, EC Number, IUPAC name etc.), secondly the fact that chemical reactions may transform the inputs during a process, and thirdly because the LCI work sometimes requires estimations on whether the properties of a previously inventoried substance can be used as an approximation for other substances. For the LCIA work the effort required firstly to determine whether a substance currently lacking a published characterisation factor should in fact have one (i.e. the toxicity of the substance is significant in the context of the study) and secondly (if necessary) to calculate the factor, is high for a non-chemist.

To overcome this situation, a hypothesis was built that a user-oriented nomenclature could simplify the understanding of LCI data for textile processes and textile chemicals for the LCA practitioner. The experiences from the Swedish Chemicals Group (Swerea IVF, 2016) were that management of chemicals in the textile supply chain by non-chemists (e.g. textile buyers/procurers with economics education) could be improved by using a nomenclature based on the functions of chemicals (introduced in section 1.1.2). A division according to functions can be made into chemicals that provide desired properties to the garment, so-called effect chemicals (colour, anti-odour properties, soft hand etc.), and chemicals that provide the desired properties for production processes, so-called process chemicals (cleaning, lubrication, conductivity etc.). A nomenclature for effect chemicals had been developed in the INKA project (Swedish Chemicals Agency, 2004). The existing nomenclature for effect chemicals was thus expanded into a more comprehensive nomenclature that also covered process chemicals.

The research process in which the nomenclature for process chemicals was developed by going back and forth between framework, data sources and analysis, was much like the systematic combining described by Dubois and Gadde (2002). Textile industry guidelines, such as the reference document on best available techniques (BAT) for the textiles industry (European Commission, 2003) and TEGEWA's international textile auxiliaries buyer's guide (TEGEWA, 2008), were used in combination with experience resulting from the case studies. The case studies included two different study trips to China to visit textile manufacturing plants. The continuous dialogue with actors from the textile industry via the Swedish Chemicals Group also contributed input. The nomenclature was developed as a categorisation of the terms found in the literature (see section 2.3) and these categories were used and refined in dialogues with actors in the supply chain. Thus the nomenclature is built on sub-sets of nomenclatures that each are accepted in their local context and here united to an entity covering the entire textile life cycle and its toxic emissions. The nomenclature, presented in Paper V, is intended to be intuitive, meaning that people should understand it without having to spend much time learning it.

3 Results and Discussion

This chapter summarises and discusses the results for the three research questions, as well as the possibilities to use LCA for governing the textile industry towards a more sustainable management of chemicals.

3.1 LCA provides unique knowledge

Research question one address whether LCA provide additional knowledge regarding toxicity impacts compared to other less time-consuming environmental assessment methods. Both Paper I and Paper II discuss how the results of LCA differ from other methods, with its quantitative approach, its life cycle perspective and its holistic view on environmental impact.

Section 1.2 of this thesis described that there are mainly two approaches for evaluation of chemical management performance in the textile industry. The first approach is to evaluate whether products pass or fail a set of given criteria (applied for example in ecolabelling). The second approach is to rank chemicals management practices, in which "scores" of some sort are given according to how well management routines are implemented (applied for example in the Higg Index). Such methods, based on qualitative assessment of textile chemicals, entail the risk that both financial and other resources are spent on implementation of management routines that contribute negligibly to any actual improvement of the environmental performance. Efforts that address the core problems for environmental performance, for example substitution of a toxic substance used in a textile factory, would in fact not always render an improved score when measuring the management performance. The efforts that do improve the score are instead development of routines, for example the development of a packaging management system or being updated on the local legislation governing the use of chemicals. Such efforts may indeed promote improvements of the core problems, but the scores will improve regardless of if they do or not.

A quantitative approach combined with a life cycle perspective avoids improving parts of a system (for example a process or an emission) in a manner that negatively affects other parts of the system (suboptimisation). The complementary knowledge for management of chemicals in the textile industry that can be gained from an LCA study concerns the comparative significance of the textile chemicals used during the textile product's life cycle. 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.

Furthermore, the textile industry faces a multitude of environmental challenges besides the impacts of chemicals. These issues include climate change, land use, depletion of water and fossil resources, as has been mentioned previously. In an LCA study a multitude of environmental impact categories are evaluated. This reduces the risk that a decision aimed at reducing chemical pollution simply shifts the environmental problem from one environmental issue to another, if chemicals are included.

It could be argued that toxicity impacts could be properly handled with a complementary qualitative analysis. However, toxicity impacts caused for example by exhaust gases from fuels and substances leaking from mining waste (as described in section 1.2.1) are already included by default in most LCA-studies, as these are included in the inventories of the existing LCI databases that are used for modelling background processes. By default the toxicity impacts of background processes are also included if the LCIA results are aggregated into a single score (weighting), as characterisation factors for these substances are included in the existing LCIA databases. The option to make a strict qualitative assessment of toxicity as a complementary assessment to the LCA is therefore not always practically possible. The consistency and comprehension of the LCA results is lacking when even the order of magnitude of the difference between the toxicity of foreground and background processes is not known. In addition, to quantitatively include toxicity impacts from some parts of the life cycle but not from all can result in misleading conclusions from LCA studies.

3.1.1 The ability to produce counter-intuitive results

The case study results in Paper I exemplify the ability to produce counter-intuitive results in an LCA study. In fact, erroneous conclusions based on intuition had been drawn prior to the case study. The intuitive conclusion had been that the unbleached product would have better environmental performance than the bleached product, since the unbleached product did not require any bleaching process. However, LCA gave a different result - that the bleached product had better environmental performance than the unbleached product, see Figure 10. The LCA study showed that the environmental impact from the bleaching was insignificant with regard to the whole garment's life cycle and was likely to be compensated for by a longer lifespan in the use phase of the bleached garment. The quantification of toxicity impacts in Paper I also showed that the implementation of waste water treatment (WWT in Figure 10) and also the choice of textile auxiliary chemicals (process chemicals in Figure 10) had greater importance than the choice of dyestuffs or the addition of bleach. This gave new information to the decision-makers setting requirements for textile procurement, which previously only targeted the dyestuffs.

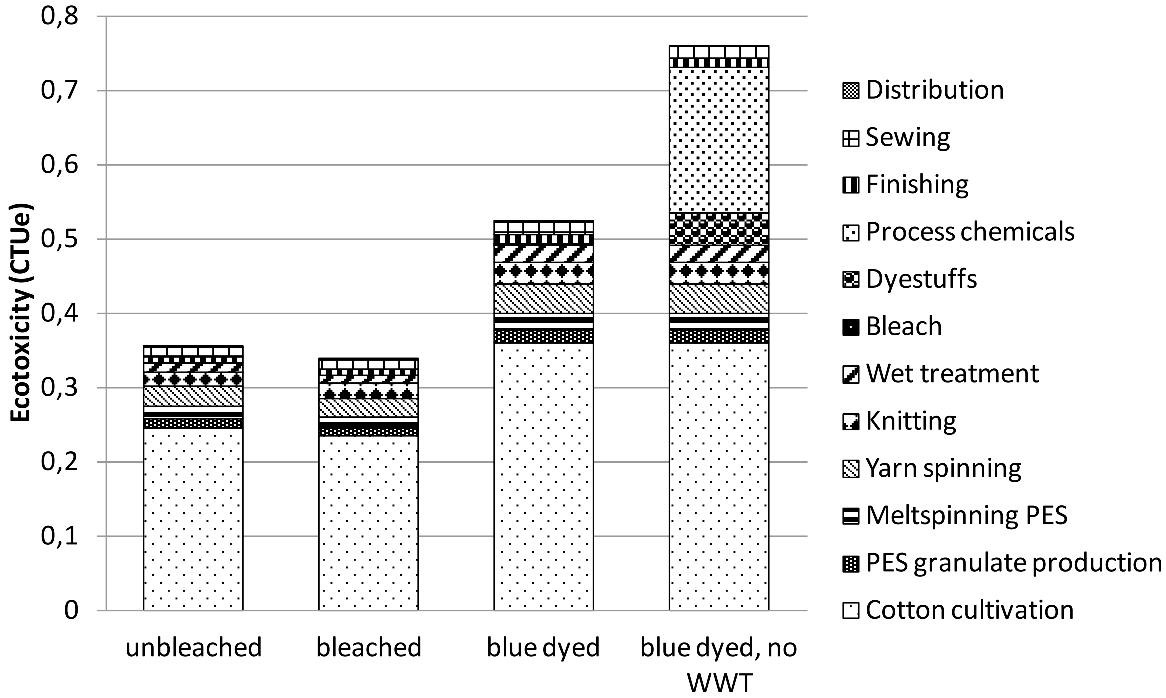

Figure 10. Results (extrapolated) for freshwater ecotoxicity for unbleached and bleached hospital night gowns and for cardigans dyed blue, with and without waste water treatment (WWT) from case study one (obtained from Paper I).

3.2 Systematizing LCI of textile products

Research question two addresses the challenge of filling the LCA data gaps in a systematic way, starting with how to identify the most important gaps to fill.

3.2.1 Identification of most important textile processes

The environmental challenges associated with consumption of textiles have been investigated on a product level in several LCA case studies in recent years (Allwood et al., 2006; Blackburn, 2009; Parisi et al., 2015; Velden et al., 2013). However, as described in section 1.1.1, there are a large variety of textile processes. In addition, the consumer behavior and end-of-life handling influence the total environmental performance of each product (Schmidt et al., 2016). One textile product is hardly representative for textile products in general.

Paper III reports a study on the shift from product level to industry sector level in the LCA of textile products. The system boundary was set to the total yearly consumption of clothes in a whole country, in this case Sweden. The industry sector approach enabled identification of the most commonly occurring materials and fabric constructions. Furthermore, these fabric constructions were modelled with the most commonly occurring textile production processes, equipments and textile-related substances. In this way, 30 LCI data sets of textile production processes were constructed, listed in Table 4. Textile chemicals have been included in the inventory for all processes in Table 4 and a BAT, average and worst case variants have been constructed.

Table 4. The 30 LCI data sets of commonly occurring textile production processes (obtained from Paper V).

Number	LCI data sets for production processes
1	Cotton fibre production
2	Polyester fibre production
3	Polyamide 6 fibre production
4	Polyamide 6,6 fibre production
5	Elastane fibre production
6	Ring spinning, CO/EL yarn 150 dtex
7	Ring spinning, CO yarn 300 dtex
8	Air-jet spinning, CO/PES yarn, 150 dtex
9	Air-jet spinning, PES yarn, 150 dtex
10	Filament DTY yarn production, 100 dtex
11	Circular knitting
12	Flat knitting
13	Weaving, 150 dtex
14	Weaving, 300 dtex
15	Non woven production
16	Bleaching cotton fabric
17	Bleaching cotton yarn
18	Dyeing denim cotton yarn
19	Dyeing polyester tricot
20	Pretreatment of polyester weave
21	Dispersion print of polyester weave
22	Dyeing polyamide weave
23	Dyeing polyester weave
24	Dyeing cotton tricot
25	Dyeing cotton weave
26	Drying and fixation of cellulosics
27	Drying and fixation of synthetics
28	Cutting
29	Sewing
30	Ironing and packaging

3.2.2 Framework for LCI including textile chemicals

Research question three addressed the challenge that even if the LCA data gaps from research question two would be filled, there will always be data gaps; the next LCA study might assess a technology or chemical outside the coverage, data will age, etc. Paper V presents the developed framework for systematizing the life cycle inventory of textile processes to enable inclusion of textile chemicals in LCA studies. The currently available LCI data sets of the framework are shown in Figure 11. All data sets can be adjusted with regard to process performance and chemicals performance on three levels: BAT, average and worst case. Five archetypal garments were also modelled (see Figure 11) with the average data sets. The LCA practitioner performing an LCA study of a textile garment can choose to either adjust the product data sets or use the process data sets separately to create a model of another product.

The framework consists of a nomenclature and a set of 30 LCI data sets. To this matching characterization factors have been developed. The model data sets are intended to be used for screening LCA studies or as data collection templates in more detailed LCA studies. Some examples of use are given in section 3.4. The framework enables LCA practitioners without chemistry background to include textile chemicals and their impact, and the consistent nomenclature will simplify the data collection and comprehension of environmental aspects of textile production. The proposed nomenclature and an example of an LCA data set (bleaching of cotton fabric) are shown in Paper V. The full framework and data sets created for this thesis are published as Supplementary Information to Paper V.

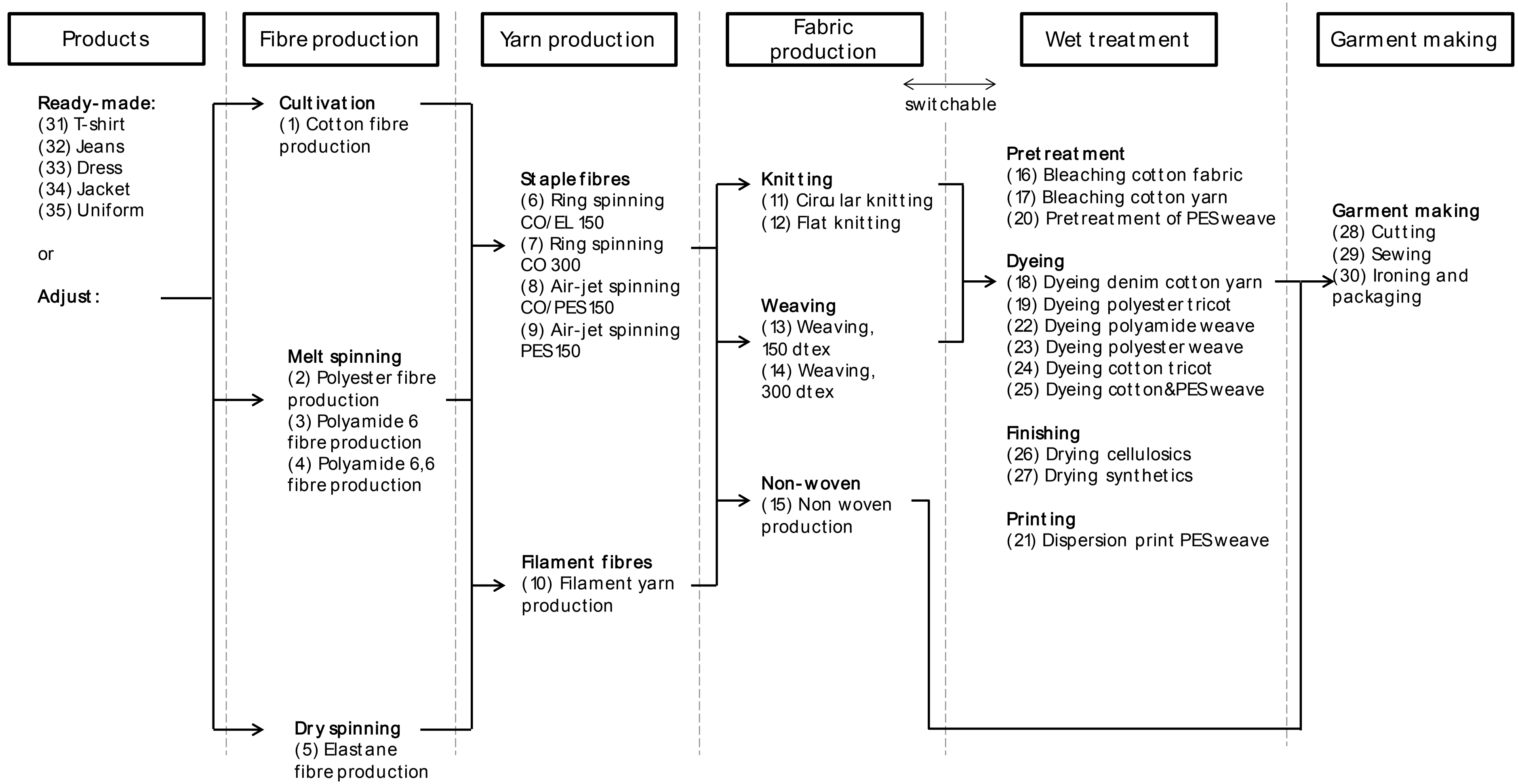

Figure 11. The LCI data sets included in the developed framework and how they can be combined in studies of specific textile products. All LCI data sets can be adjusted regarding process and/or chemicals performance on three levels: best available technology (BAT), average and worst case.

3.3 Characterisation factors for textile chemicals

The overarching purpose with the method development regarding LCIA is to facilitate further calculation and application of characterisation factors for textile chemicals in the future and ensure that LCA results can provide relevant guidance towards the environmentally sustainable management of chemicals in the textile industry.

Paper I shows examples of studies where a thorough inventory has been made of textile chemicals in the LCI step, but the emissions related to these chemicals were not included in the LCIA since there were no characterisation factors to match them. Paper II and IV both show that it is difficult to estimate in advance which substances will be most significant according to the USEtox model, and Paper IV recommends that characterisation factors are calculated for all textile-related substances.

A gross list of textile-related substances that would need characterisation factors for inclusion in LCA of textile products resulted from the inventories of the textile chemicals used in the processes from Paper III (Table 4). The list was complemented with some common transformation products. These are substances that are either formed by intended or unintended chemical reactions involving textile chemicals or by-products from the degradation of textile chemicals in the environment and the human body. In some cases the textile-related substances are also impurities that commonly occur in these textile chemicals. The full list comprises 72 substances and is shown in Table 5. The nomenclature from section 2.4 is used to categorise the textile-related substances.

Out of the 72 listed substances, 47 were found to have ready-made characterisation factors in either the USEtox 2.01 database or the COSMEDE database (ADEME, 2015). COSMEDE is a database with USEtox characterisation factors for detergent and cosmetics chemicals. The remaining 25 (highlighted in bold and italics in Table 5) were prioritized for filling the data gaps on characterisation factors.

Table 6 presents the new USEtox characterisation factors for 25 textile-related substances. All characterisation factors are regarded as indicative; thus, if they are going to be used for more than screening purposes they should be further verified.

Table 5. List of prioritized substances for inclusion in LCA of textile products. 25 substances highlighted in bold and italics did not have a characterisation factor in either the USEtox 2.01 or the COSMEDE databases. PC = precursor. TP = transformation product. DWR = durable water repellent.

Substance function	CAS RN	Substance name
Acid A	64-18-6	Formic acid
Acid B	64-19-7	Acetic acid
Acid C	7664-93-9	Sulfuric acid
Antifoaming agent A	151-21-3	Sodium lauryl sulphate
Antifoaming agent B	***67762-90-7***	***Dimethyl siloxane, reaction product with silica***
Base A	1310-73-2	Sodium hydroxide
Base B	497-19-8	Sodium carbonate
Bleach A	7722-84-1	Hydrogen peroxide
Decalcifier A	7783-20-2	Ammonium sulphate
Detergent A	126-92-1	Sodium mono(2-ethylhexyl)estersulfate
Detergent B	143-22-6	2-[2-(2-butoxietoxi)etoxi]etanol
Detergent C	69011-36-5	Isotridecanol ethoxylated
Dispergent A	68439-46-3	C9-11 Alcohol ethoxylate
DWR agent A	8002-74-2	Paraffin Wax
DWR agent B	9002-92-0	Poly(oxy-1,2-ethanediyl), α-(1-oxooctadecyl)-ω-hydroxy-
DWR agent C	***63148-62-9***	***PDMS***
DWR agent D	***27905-45-9***	***1H,1H,2H,2H-Perfluorodecylacrylate (8:2 FTA)***
Dyestuff A	1937-37-7	Direct Black 38
Dyestuff B	482-89-3	Indigo
Dyestuff C	577-11-7	Yellow disperse dyestuff PA
Dyestuff D	***20721-50-0/ 12222-69-4***	***C.I. Disperse Black 9***
Dyestuff E	***149850-30-6***	***metyl-N-[(3-acetylamino)-4-(2-cyano-4-nitrofenylazo)fenyl]-N-[(1-metoxi)acetyl]glycinat***
Dyestuff F	***81-42-5***	***Disperse Violet 28***
Dyestuff G	***204277-61-2***	***Alanine, N-[5-(acetylamino)-4-[(2-chloro-6-cyano-4-nitrophenyl) azo]-2-methoxyphenyl]-N-(2-methoxy-2-oxoethyl)-, methyl ester***
Dyestuff H	***13324-20-4***	***Reactive Blue 4***
Dyestuff I	***522-75-8***	***2-(3-oxobenzo[b]thien-2(3H)-ylidene)benzo[b]thiophene-3(2H)-one***
Dyestuff J	***59312-61-7***	***1,2-dihydro-6-hydroxy-1,4-dimethyl-2-oxo-5-[[3-[(phenylsulphonyl) oxy]phenyl]azo]nicotinonitrile***
Dyestuff K	***6054-48-4***	***Disperse Black 1***

Substance function	CAS RN	Substance name
Lubricant A	***25085-02-3***	***Acrylamide/sodium acrylate copolymer (Polyacrylamide (PAM))***
Optical brightener A	16470-24-9	Fluorescent Brightener 220
PC A[1]	111-42-2	Diethanolamine
PC B[2]	541-02-6	D5, Decamethylcyclopentasiloxane
PC C[2]	556-67-2	D4, Octamethylcyclotetrasiloxane
Penetration agent A	9016-45-9	Ethoxylated alcohol (NPEO)
Peroxide stabilizer A	7786-30-3	Mg2Cl2
Plasticizer A	142-16-5	Maleic acid, bis(2-etylhexyl)ester
Preservative A	26172-55-4	5-chloro-2-methyl-4-isothiazoline-3-one
Preservative B	2682-20-4	2-methyl-4-isothiazolin-3-one
Salt A	7757-82-6	Sodium sulphate
Salt B	7772-98-7/ 10102-17-7	Thiosulfate
Sizing agent A	9002-89-5	Polyvinyl alcohol
Soda A	471-34-1	Calcium carbonate
Softener A	107-41-5	Hexylene glycol
Solvent A	104-76-7	Isooctyl alcohol
Solvent B	107-21-1	Ethylene glycol
Solvent D	112-30-1	Decanol
Solvent E	64742-47-8	Decane and other higher alkanes
Solvent F	67-64-1	Aceton
Solvent G	68526-86-3	Alcohols, C11-14-iso-,C13-rich
Stabilizer A	69011-36-5	Isotridecanol ethoxylated
Stabilizer B	***13708-85-5***	***Phosphonic acid, disodium salt***
Surfactant A	***37251-67-5***	***Oxirane, methyl-, polymer with oxirane, decyl ether***
Surfactant B	***93348-22-2***	***Fatty methylester sulfonates (R16)***
Surfactant C	***9046-01-9***	***Poly(oxy-1,2-ethanediyl) , .alpha.-tridecyl-.omega.-hydroxy-, phosphate***
Surfactant D	***137-20-2***	***Sodium 2-[methyloleoylamino]ethane-1-sulphonate (cis-isomer)***
Thickener A	64742-48-9	Naphtha, petroleum, hydrotreated heavy
Thickener B	64742-54-7	Distillates, petroleum, hydrotreated heavy paraffinic
TP A[3]	17527-29-6	1H,1H,2H,2H-Perfluoroctylacrylate (6:2 FTA)
TP B[4]	25154-52-3	Nonyl phenol
TP C[5]	50-00-0	Formaldehyde
TP D[6]	75-21-8	Ethylene oxide

Substance function	CAS RN	Substance name
TP E[5]	79-06-1	Acrylamide
TP F	***1066-40-6***	***Hydroxytrimethylsilane (trimethylsilanol) (TMS)***
TP G	***1066-42-8***	***Dimethylsilanediol (DMSD)***
TP H	***2043-47-2***	***1H,1H,2H,2H-Perfluoro-1-hexanol (4:2 FTOH)***
TP I	***307-24-4***	***Perfluorohexanoic acid (PFHxA)***
TP J	***335-67-1***	***Perfluorooctanoic acid (PFOA)***
TP K	***375-73-5***	***Perfluorobutane sulfonic acid (PFBS)***
Wetting agent A	61827-42-7	Ethoxylated fatty alcohol
Wetting agent B	***78330-23-1***	***Fatty alcohol alkoxylate***
Wetting agent C	***3055-94-5***	***Lauryl alcohol di(oxyethylene) ethanol***

[1] Precursor to Softener A
[2] Precursor to silicon based DWR agents
[3] Transformation product of DWR agent B
[4] Transformation product of Penetration agent A
[5] Transformation product of Stabilizer A
[6] Transformation product of Detergent C

Table 6. New characterisation factors for 25 textile-related substances calculated with USEtox 2.01 and the main source of uncertainties (explanations in footnotes). PC = precursor. TP = transformation product. DWR = durable water repellent. NEG = the toxicity can be considered negligible based on available information. DG = data gap. * = minimum data quality. From Paper IV.

Substance	CAS RN	Human toxicity, cancer [CTUh]	Human toxicity, non-cancer [CTUh]	Freshwater ecotoxicity [CTUe]	Main sources of uncertainty
Antifoaming agent B	67762-90-7	NEG*	1.26E-09*	4.74E-02	II, III
DWR agent C	63148-62-9	NEG*	3.69E-09	1.29E+01*	
DWR agent D	27905-45-9	NEG	1.58E-06*	4.84E+00*	VII, VIII
Dyestuff D	20721-50-0 /12222-69-4	NEG*	6.10E-09*	4.74E+00	IV
Dyestuff E	149850-30-6	NEG	8.16E-10	3.41E+01	VIII
Dyestuff F	81-42-5	3.85E-08	1.15E-09	5.70E+02	IV, V, VI
Dyestuff G	204277-61-2	NEG*	2.03E-10	1.43E+03	II, VIII
Dyestuff H	13324-20-4	4.00E-09*	4.09E-11	2.92E-02	IV
Dyestuff I	522-75-8	4.14E-05	1.93E-08	4.63E+02*	IV,V
Dyestuff J	59312-61-7	DG	5.24E-11	3.52E+01*	V
Dyestuff K	6054-48-4	1.81E-07	1.68E-09	8.19E+01	IV, V
Lubricant A	25085-02-3	DG	8.31E-12	1.68E+01	II, III
Stabilizer B	13708-85-5	DG	2.03E-08*	1.48E+03*	VIII
Surfactant A	37251-67-5	DG	3.59E-09*	1.11E+02	II
Surfactant B	93348-22-2	DG	1.40E-08	3.20E+04*	VI
Surfactant C	9046-01-9	DG	4.10E-10*	1.44E+03*	
Surfactant D	137-20-2	NEG	5.11E-09*	6.08E+02*	VII
TP F	1066-40-6	NEG*	9.13E-09*	7.08E+00*	VIII
TP G	1066-42-8	NEG	5.46E-09	4.87E-01	VII
TP H	2043-47-2	NEG	5.54E-07	6.45E+01	I, VII
TP I	307-24-4	NEG*	2.06E-07*	5.15E+01*	
TP J	335-67-1	1.40E-03*	1.57E-04*	1.13E+02*	
TP K	375-73-5	NEG	2.82E-07*	7.55E+01	II, VII
Wetting agent B	78330-23-1	1.27E-07	8.72E-09	5.22E+03*	
Wetting agent C	3055-94-5	1.90E-08	2.06E-09*	4.77E+03	II

I = Estimated data outside valid domain
II = Ecotoxicity data do not cover three trophic levels
III = Expert judgement
IV = (Q)SAR and/or categorisation/grouping method not robust/reliable for this substance
V = The substance may not be soluble enough to measure the predicted ecotoxicological effect(s).
VI = Read-across for repeated dose toxicity (non-cancer) based on fewer than 5 analogues
VII = Data gap is filled by acute to chronic extrapolation or categorised as NEG as recommended in Rosenbaum et al.(Rosenbaum et al., 2011)
VIII = EC50 could not be determined (> data used).

3.3.1 Pitfalls in calculating characterisation factors for textile chemicals

The modelling of persistence of organic chemicals in USEtox was identified in Paper II as a topic that needed further investigation. Several types of textile chemicals are intentionally designed to be persistent (e.g. dyes, optical brighteners and water-repellent agents). The legislative frameworks of the CLP (European Commission, 2008) and REACH (European Commission, 2006) regulations both reflect a concern about very persistent and very bioaccumulating chemicals (so called vPvBs). These properties on their own are enough for a classification as substance of very high concern (SVHC). In the case study in Paper II an optical brightener with persistent properties was included and scored highly with the CLP-based methods (Score System and The Strategy Tool). The USEtox characterisation factor for the same substance was however very low, which shows that the property of environmental persistence of organic chemicals is not considered to be as important in this method.

In Paper IV a sensitivity analysis was performed investigating the influence of the different input parameters. The sensitivity analysis is performed on two levels: 1) studying the impact of the numerical values of the input parameters, and 2) studying the impact of the data source selection for the input parameters.

Paper IV shows the results of varying the numerical values of input parameters by two order of magnitudes up or down. It must be pointed out that many of these parameter values are not possible to find in real-life measurements. This sensitivity analysis is only theoretical and has the purpose of exploring which input parameters are the main sources of uncertainty for different types of chemicals. The input parameters to which the characterisation factors are sensitive can then be examined in greater detail in the next step, while default values can be used for the others.

The freshwater ecotoxicity characterisation factor is very sensitive to the value of the toxicity impact parameter (termed avlogEC50 in USEtox). This reflects that the effect factor (EF) has linear relational impact on the characterisation factors for all substances (see Eq. 3). Another input parameter of almost equally high importance is the degradation rate in water (KdegW). The substances for which the characterisation factors were observed to vary most with the water degradation rate are the more persistent ones (e.g. the dyestuffs). Likewise, the substances for which the characterisation factors were observed to vary most with the octanol/water partition coefficient (K_{ow}) and dissolved organic carbon/water partition coefficient (K_{DOC}) values are those with high K_{ow} and/or K_{DOC}. The characterisation factors that are sensitive to the value of the input parameters for the acid dissociation constant (pKa) are the perfluorinated acids PFOA, PFHxA and PFBS (transformation products of DWR agents). Other input parameters contribute very little to the uncertainty of the freshwater ecotoxicity characterisation factor result.

For human toxicity, the characterisation factor was likewise seen to be very sensitive to the value of the toxicity impact parameter (termed ED50 in USEtox). In the case of emissions to urban air, degradation rate in air is moderately important but the other degradation rates have quite low contribution. However, in the case of emissions to freshwater, degradation rate in water is very dominant. Thus, the dependency on the emission compartment is stronger for the human toxicity scores than for the ecotoxicity scores. A third important parameter for human toxicity scores is the bioconcentration factor for fish (BAF_{fish}).

The second step of the sensitivity analysis explored the impact of using more accurate input data with the USEtox model for a specific substance group: per- and polyfluoroalkyl substances (PFAS). For PFAS, the EPI Suite estimation routines are not applicable and therefore experimental data were retrieved from literature. The USEtox manual (Huijbregts et al., 2015c) recommends (put in simplified terms) using data from the EPI Suite^{TM}, primarily experimental data (if available) and secondarily modelled data. Gouin et al. (2004) have shown that the persistence of more persistent chemicals is often underestimated in the EPI Suite^{TM}. However, the impact from varying the fate parameter data using literature data was shown to be very low for emissions to freshwater and insignificant for emissions to air and soil. The added value of collecting literature data for fate-related input parameters for USEtox, instead of using the EPI Suite model, was therefore concluded to be moderate in relation to the added workload for the LCA practitioner. It was further concluded that for fate parameters it is not the data source selection but the fate model in USEtox that needs to be developed in order to give a better appreciation of the persistence of organic chemicals in USEtox. The USEtox model could be developed to more accurately depict the long exposure scenario for persistent organic pollutants (POPs).

Paper IV concludes that in USEtox the inherent toxicity of the chemical is the input parameter that contributes most to the resulting characterisation factor, which is also supported by other literature (Alfonsín et al., 2014; Henderson et al., 2011; Igos et al., 2014). A best-estimate for the input value of the toxicity is therefore vital for a correct characterisation factor.

3.3.2 Data source selection strategy for calculating characterisation factors

Research question three is formulated from the context that even if the LCA data gaps from research question two were currently filled, there would always be data gaps, i.e. the next LCA study might assess a technology or chemical outside the coverage, data will age, etc. Paper IV therefore provides not only ready-to-use characterisation factors for the full set of common textile chemicals, but also presents a data source selection strategy for input data for the USEtox model, see Figure 12 (obtained from Paper IV).

The data source selection strategy is a three-step process. Step I is to search for data in the USEtox endorsed databases, i.e. those listed in the USEtox manuals (Huijbregts et al., 2015a, 2015b, 2015c), giving priority to the user manual. If a complete data set (aquatic ecotoxicity data that covers three trophic levels and/or human health cancer and/or non-cancer effects, depending on the goal of the study) is achieved, the data search is done. In Step II, experimental data is retrieved from other data sources that can provide minimum data quality, primarily those in eChemPortal (OECD, 2016). In Step III, for parameters where experimental data of minimum data quality were not available, a Weight-Of-Evidence (WOE) approach was used that combined estimated data from the application of QSAR or other estimation methods and insufficient experimental data. Table 7 describes the criteria for minimum data quality as defined in Paper IV. The criteria are based on the Klimisch scoring system is a commonly used method for assessing the reliability of toxicological studies (Klimisch et al., 1997).

The data source selection strategy provides a structured and transparent way to calculate characterisation factors for textile chemicals in USEtox. The strategy both promotes compatibility with the USEtox manuals and input data of a defined level of minimum data quality, while keeping the workload to a minimum for the LCA practitioner. The importance of accessing the background data and explaining the choice of data sources in a transparent way to increase opportunities for future studies and improvements is highlighted. The user of the resulting LCA will then have the chance to understand shortcomings and limitations in the results.

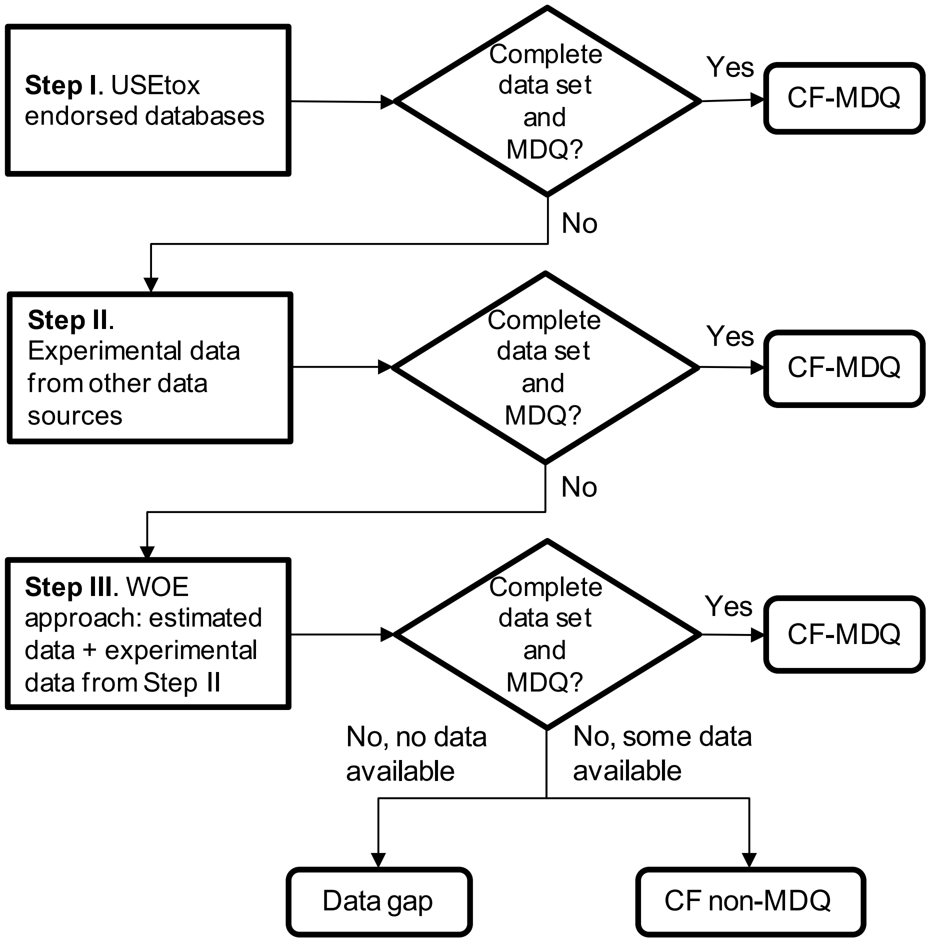

Figure 12. The three step data source selection strategy presented in Paper IV. MDQ = minimum data quality.

Table 7. Criteria and categorisation for data quality assessment. WOE = weight-of-evidence. MDQ = minimum data quality. CF = characterisation factor.

Data quality category	Comment	MDQ
Step I		
A	Data collected in an identical process as the one outlined in the USEtox manuals are automatically considered MDQ since the CFs are aimed to be as similar as the USEtox CFs as possible.[1]	YES
Step II		
B	Data ranked as Klimisch score 1 and 2 (including industry self-ranking), i.e. a well-performed study with complete documentation.	YES
C	Data peer-reviewed by a reliable third party (e.g. from articles in peer-reviewed scientific journals or reports published by an authority or other competent body), which is believed to use assessment criteria equivalent to Klimisch scores 1 and 2.	YES
D	Data ranked as Klimisch score 3 and 4 (including industry self-ranking), i.e. a study not relevant for the purpose and/or of low quality or lacking complete documentation.	NO
Step III		
E	Data calculated with an estimation method relevant for the chemical structure, e.g. the substance is within the application domain for the (Q)SAR-model, and based on a robust/reliable grouping/categorisation and /or (Q)SAR.	YES[2]
F	Data calculated for a substance outside the application domain of the (Q)SAR or by a grouping/categorisation and/or (Q)SAR that is not reliable/robust.	NO[2]

[1] Data in category A can be considered non-MDQ if substance-specific properties indicate that the method is not appropriate, e.g. BCF estimation based on K_{ow} for substances for which K_{ow} is not a relevant measure, e.g. the PFASs (Armitage, 2009).

[2] Estimated data (data quality category E, F) are used together with experimental data from Step II in a weight-of-evidence approach when sufficient experimental data to arrive at CF-MDQ are not available, i.e. if available data are of low quality (data quality category D) or do not cover all relevant species/endpoints (data quality B, C), see Figure 12.

3.4 Application of results in LCA of textile products

Paper V demonstrates two examples of the results that can be calculated based on the developed framework. Firstly the current sustainability performance of the Swedish apparel sector is modelled, based on the industry sector approach from Paper III. Secondly the effects of interventions for environmental impact reduction are explored, based on results from Papers III, IV and Paper V.

3.4.1 Determining the current sustainability performance of the Swedish apparel sector

Paper III reports the current environmental impact of the total yearly Swedish clothing (textiles other than apparel excluded) consumption in terms of carbon footprint and scarcity-weighted water use. Paper V adds the freshwater ecotoxicity impact category. Figures 13-15 show the contribution from the different life cycle phases for potential environmental impact in terms of carbon footprint, scarcity-weighted water use and freshwater ecotoxicity. In particular the inclusion of the freshwater ecotoxicity results has been enabled by the work in this thesis. Results of this kind can be used to identify the types of interventions that may be more successful in reducing the environmental impacts, as the results gives a quantitative comparison. Figures 13-15 show absolute values for the Swedish clothing sector. It is important to note that there is a considerable amount of uncertainty in these absolute values.

The carbon footprint of the Swedish clothing sector over one year was calculated to be 2.45 million tonnes CO_2-equivalents per year in Paper III, or approximately 0.25 tonnes CO_2-equivalents per capita and year. The average carbon footprint for a Swedish person is around 10 tonnes of CO_2-equivalents per year (Larsson, 2015), which means that the carbon footprint share from fashion is currently only 2.5%. However, in a sustainable future where the 2 degree goal is reached, IPCC anticipates that global annual greenhouse gas emissions will have to be reduced by 14–96% by 2050 compared to the emission levels of 1990, and that emissions must be close to zero by 2100 (scenario RCP2.6 in (IPCC, 2013)). The authors behind the planetary boundary framework suggest that an atmospheric concentration of 350 ppm CO_2 (corresponding to about 400 ppm CO_2-eq.) corresponds to a safe level for humanity (using the precautionary principle (Steffen et al., 2015)), which would probably require even lower per capita emissions by 2050 than those that are indicated by the IPCC scenario as corresponding to the lowest emissions. Regardless of the approach, this means that the climate impact from textile consumption needs to be reduced considerably in a sustainable future. Figure 13 shows that the most significant life cycle phase for climate impact is fabric production (including wet treatment), followed by the transport of the garment from the retailer to the user's home (use phase transport).

Regarding scarcity-weighted water use, it is clear from Figure 14 that cotton fibre production dominates this impact category. The water use figures are weighted using the Swiss Ecoscarcity model (Frischknecht et al., 2008) based on the scarcity of the water in the country where it is used. The use of water for washing clothes in Sweden is therefore not significant, since there is freshwater abundance in Sweden. Cotton production on the other hand frequently leads to severe water stress as the extraction of irrigation water often occurs in freshwater-scarce areas. Water use in the fabric production stage has also an insignificant contribution according to Figure 14, since the producing countries do not suffer from water scarcity at the national scale. However, it should be noted that local scarcity of water does exist, which is not captured by this way of performing LCA with national average data for water scarcity. Neither is water quality included in the water scarcity impact category. The total “water footprint” of the Swedish clothing sector over one year was calculated to be 1050 million cubic metre equivalents, or approximately 100 cubic metre equivalents per capita and year.

Figure 15 shows the potential contribution to freshwater ecotoxicity from the Swedish clothing sector over one year. The contribution was calculated to 7.9 billion CTUe, whereof 5.5 billion CTUe origins from background processes and 2.4 origins from direct emissions in foreground processes. It can be seen that the wet treatment stands for the largest contribution to freshwater ecotoxicity impact. Second most important is the cotton fibre production, followed by the yarn production. It should be noted that emissions of substances in the use phase (mainly household detergents) have not been inventoried here.

The 7.9 billion CTUe can be interpreted as 7.9 cubic kilometres of freshwater where 50% of the species in the ecosystem are exposed daily to a concentration above their EC50 (half maximal effective concentration, e.g. the concentration at which 50% of a population dies in a laboratory test) as a result of the Swedish clothing consumption. The volume of freshwater in all the lakes and rivers (where freshwater species live) on the planet amounts to 93 113 km^3 (U.S. Geological Survey, 2016). Thus, the share severely polluted (50% of the species in the ecosystem are exposed daily to a concentration where 50% of the population dies) by Swedish clothing consumption would be 0.009% of the total freshwater volume. Roughly, if all people globally would consume clothes the same way as Swedish people, 6% of the global freshwater volume would be severely polluted just from the textile industry (which is holding a share of around 4% of the global merchandise trade).

It is clear in Figure 15 that the toxicity contributions from background processes in the model (exhaust gases from fuel combustion and leakage of substances from mining waste) dominate the freshwater ecotoxicity impacts and these are a large source of uncertainty. In the end-of-life phase, a negative result is noted since the garments are assumed to be burned with energy recovery giving credits for substituted energy production (Roos et al., 2015). Thus the results for toxicity impacts depend on the modelled substituted energy production. Other end-of-life options such as reuse and material recycling would render different results which could be further explored.

In section 1.2.1 it was discussed that the chemical substances included most comprehensively in LCI databases are chemicals related to energy production, since inventories for energy production have been studied intensively (Beck et al., 2000). However, in these inventories the emissions of substances with potential toxicity impacts have often been estimated (Ecoinvent, 2010). To give an example, in the ecoinvent process for Chinese electricity (“CN: electricity, medium voltage, at grid”) the ecotoxicity impact result is dominated by three disposal processes: “Disposal, hard coal ash, 0% water, to residual material landfill/PL”; “Disposal, spoil from coal mining, in surface landfill/GLO”; and “Disposal, tailings from hard coal milling, in impoundment/GLO”. The disposal of hard coal ash in this Chinese electricity production data set is modelled with a process from 2000 that is valid for Poland. This data set in turn contains an estimated emission of 0.35 mg vanadium per kg disposed ash, which contributes to around 25% of the total toxicity for Chinese electricity production. In 2012 China produced 3 785 TWh electricity from coal (IEA, 2014). This would mean that in China 0.35 tonnes of vanadium would leak out of hard coal ash landfills each year. This figure can be compared with the total US production in 2012 of 106 tonnes of vanadium (U.S. Geological Survey, 2015). The real Chinese electricity production is probably less toxic than the ecoinvent database data suggests.

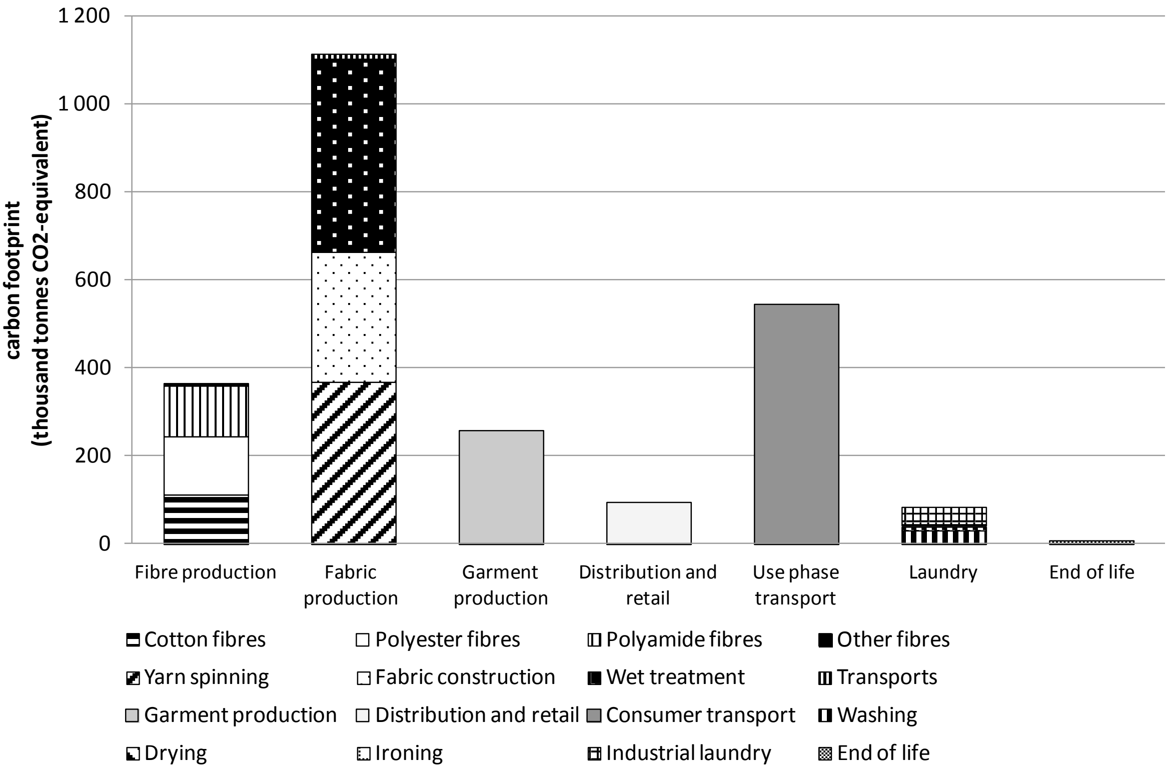

Figure 13. Carbon footprint of the Swedish apparel sector over one year. The results are divided into different life cycle phases, and the contribution from different processes (from Paper III).

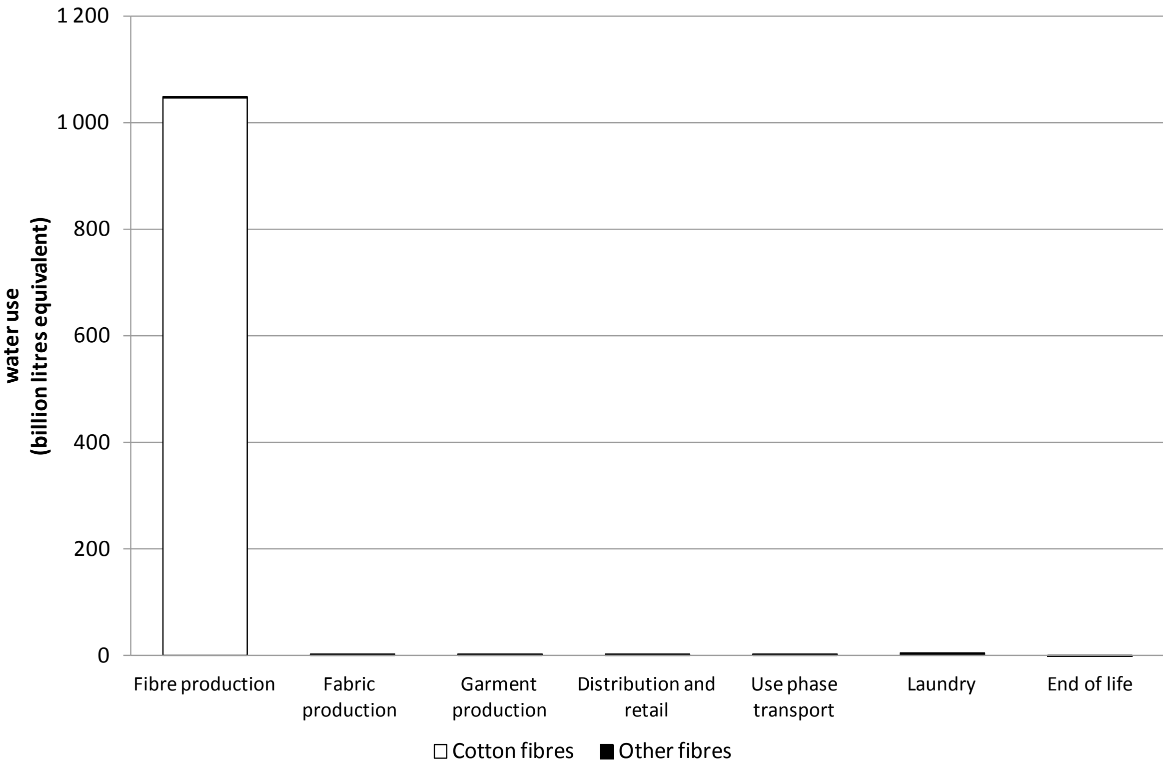

Figure 14. Scarcity-weighted water use for the Swedish apparel sector over one year. The results are divided into different life cycle phases and fiber types (from Paper III).

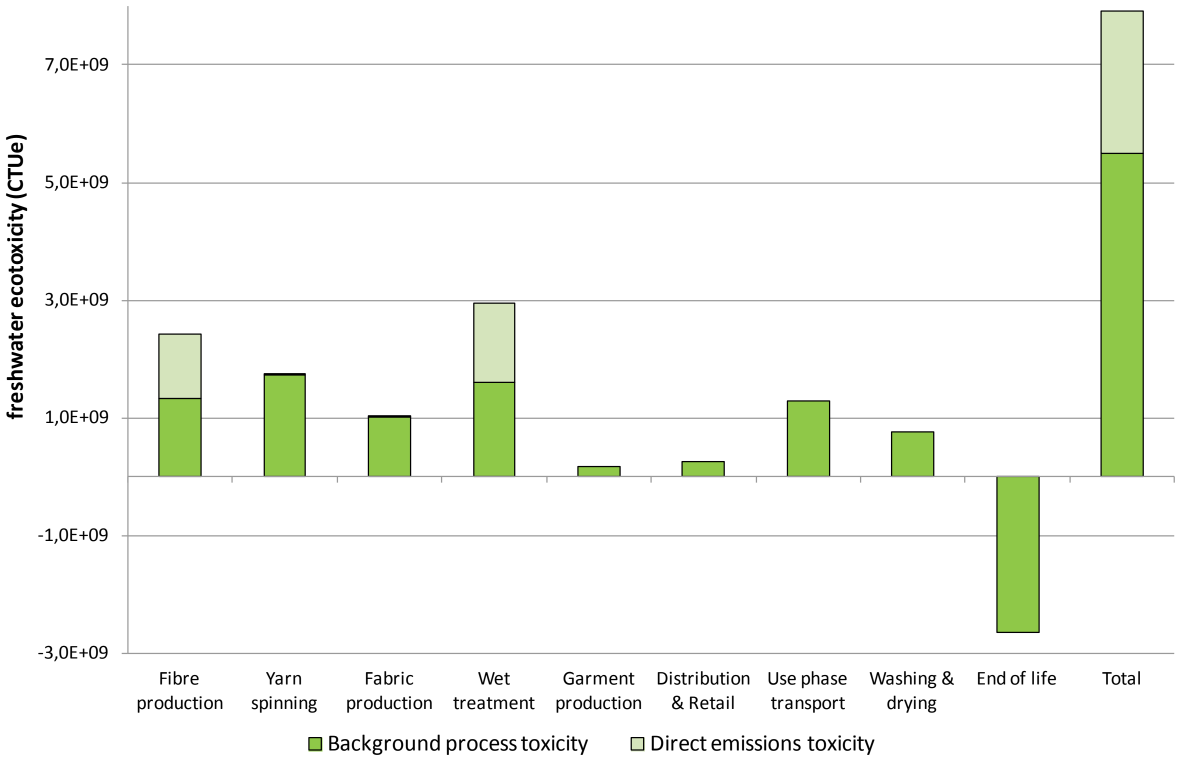

Figure 15. Freshwater ecotoxicity impacts from the Swedish apparel sector over one year. The results are divided into different life cycle phases and whether the toxicity originates from direct emissions in foreground processes or from background processes (from Paper V).

3.4.2 Effects of interventions for environmental impact reduction

The strategy for improving the environmental performance differs between organizations, industry sectors and countries. The selection of strategy is seldom straightforward and typically involves trade-offs between different environmental aims; climate mitigation, a non-toxic environment, resource conservation etc. Several alternative solutions (technical and policy-related) on how to improve the environmental performance are often presented. These solutions are mostly related to the Affluence (A) and the Technology (T) parameters of the IPAT equation (Eq. 1). LCA offers the possibility to quantitatively evaluate *how much* the environmental performance is improved, thereby avoiding spending time, money and effort on interventions that will not lead to more than marginal improvements. LCA can also help prioritize between interventions, as well as explain how application of several interventions from a multitude of actors will impact the total environmental performance.

Potentials to reduce the environmental impact of clothing consumption in Sweden for ten different interventions are presented in Figure 16 for freshwater ecotoxicity. The different interventions are described in Paper III, where results for carbon footprint and water use can also be found. Figure 16 shows that the interventions have very different potentials to reduce freshwater toxicity impacts. In the case of collaborative consumption based on physical (offlines) stores or libraries (intervention 1), the freshwater toxicity impact might in fact increase 42% due to consumers travelling more often to and from the store (under certain transportation assumptions). The online collaborative consumption scenario (intervention 2) sees a 21% decrease in contributions to freshwater ecotoxicity potential. The polyester and mechanical cotton recycling scenarios reduce the ecotoxicity burden less than 5% (interventions 3 and 4). The replacement of cotton fibres with lyocell fibres from either recycled cotton or from forest resources gives similar results, a 25% reduction of freshwater toxicity impacts (interventions 5 and 6). Intervention 7 (which assumes that consumers reduce their apparel consumption by half) and intervention 8 (a transition to renewable energy sources throughout the life cycle) are the most effective interventions to reduce freshwater ecotoxicity impacts (more than 60% reduction). Increased energy efficiency in garment production (intervention 9) and human-powered transport (intervention 10) to and from the store potentially reduce the impact with 14 and 16% respectively. It is generally possible to combine several of the interventions.

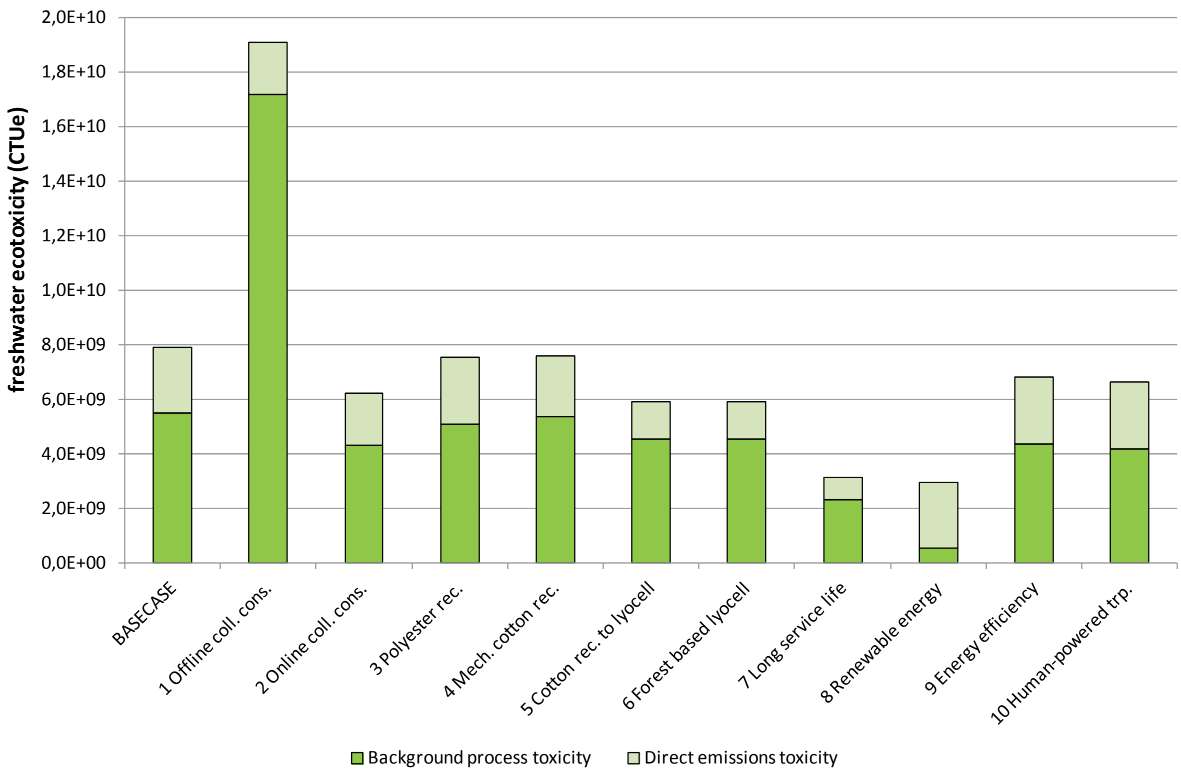

Figure 16. The reduction (or increase) compared with the base case in freshwater ecotoxicity impact potential for the Swedish apparel sector over one year as a result of the different interventions, calculated with USEtox 2.01.

3.5 Future work

This section describes the delimitations of the work performed within the scope of this thesis, as well as some general weaknesses of the methodologies used.

3.5.1 Additional aspects

The current framework has been developed for the purpose of enabling a holistic assessment of the environmental impact of textile products with LCA. The improvements of inventory data and impact assessment have mainly focused on including textile chemicals and their toxicity impacts. As a consequence some aspects are not included.

Textile chemicals and textile-related substances are also known to contribute to other environmental impact categories in addition to toxicity, such as global warming potential and acidification potential. These impacts are not considered in this thesis.

The focus has been on the textile production processes. Toxicity impacts from, for example, the production of chemicals have been included but not studied in detail within the scope of this thesis and neither have the toxicity impacts from background processes, although they are reported as very important contributors to the toxicity scores. The modelling of toxic emissions in the background processes need to be investigated further to give more clarity to what drives the toxicity impacts and what would be the most effective interventions for textile products.

All materials that can be found in textile products have not been considered in this work. Such materials include leather and wool. Further studies to investigate toxicity impacts of such materials are recommended.

3.5.2 Further development of USEtox

The USEtox model was selected for calculation of toxicity impacts in this thesis as it is a broadly used and recommended and was developed as a consensus model (see 2.1.5). Similarly to other models, USEtox has its weaknesses and has been criticized for them (Westh et al., 2015). Owsianiak et al. (2014) showed for example that the USEtox, USES-LCA and IMPACT 2002+ models for LCIA often render different toxicity scores when compared. Paper II includes a discussion of how the toxicity scores differ between USEtox and simplified methods based on hazard phrases, with a comparison of which weakness is preferable: the inaccuracy associated with having a more complex model with a more realistic representation of environmental processes but larger risk for errors due to data gaps or incorrect use, or the inaccuracy associated with using less data-intensive methods based on semi-quantitative association of hazard statements that are less representative of environmental processes.

Section 2.14 brought up general objections to the method. A specific criticism concerns metals, which are known to be a problematic substance group for USEtox (Hauschild et al., 2011), especially essential metals. Zinc is a metal for which USEtox gives a much higher toxicity potential than USES-LCA (Heimersson et al., 2014). Nordborg et al. (2017) describes the paradox that USEtox pinpoints zinc as a major contributor to the human toxicity impact potential, while it has at the same time been described as “relatively harmless” (Plum et al., 2010). Such paradoxes need to be resolved.

4 Conclusions

This thesis describes an attempt at solving the problem that LCA studies of textile products often report incomplete toxicity impact potential results. The emissions of toxic chemicals from textile production are an important environmental aspect to include in LCA studies of textile products.

Based on the findings in Papers I and II, the answer to the first research question is positive. LCA does provide additional knowledge compared to both qualitative management routines, focused evaluation procedures and simplified semi-quantitative methods. The main advantage of using LCA to assess the toxicity impact potential of textile chemicals, compared to other methods, is that there is potential for the environmental performance to be expressed quantitatively. When correctly performed (including textile chemicals in both LCI and LCIA), the quantitative toxicity assessment that is carried out in an LCA allows for comparison of the effectiveness of different routines for the management of chemicals. LCA can thus guide product procurers, designers and other environmental decision-makers to take environmentally sound decisions. A rationale for further method development to facilitate inclusion of the potential toxicity impacts from textile chemicals in LCA studies was hence established.

The second research question addresses the challenge of filling the LCA data gaps in a systematic way, starting with how to identify the most important gaps to fill. Paper III explored the shift from product level to industry sector level in LCA for textile products. By including the total yearly consumption of clothes in a whole country within the system boundaries, in this case Sweden, the most commonly occurring textile processes were identified in Paper III.

The second research question also addresses characterisation factors for the substances emitted from textile processes. Paper I showed examples of studies where a thorough inventory had been made of textile chemicals in the LCI step, but the emissions related to these chemicals were not included in the LCIA, since there were no characterisation factors for them. Papers II and IV both show that it is difficult to estimate beforehand the substances that will be most significant when applying the USEtox model, and Paper IV recommends that characterisation factors are calculated for all textile-related substances in LCA studies of textile products.

The third research question infers a new challenge, i.e. even if the LCA data gaps from research question two were to be filled there will always be data gaps; the next LCA study might be assessing a technology or chemical outside the coverage, data will age, etc. Paper V presents a framework for systematizing life cycle inventory of textile processes to enable inclusion of textile chemicals in LCA studies of textile products. The framework is populated with 30 LCI data sets, and two illustrative examples on how to use the framework is provided in Paper V. Paper IV presents a set of USEtox characterisation factors for the most commonly occurring textile chemicals (matching the inventories of Paper V) and a data source selection strategy for future calculation of characterisation factors with the USEtox model.

From the LCI point of view, the answer to the third research question is that the framework presented in Paper V can be used by LCA practitioners who are non-experts in textile technology and chemistry to facilitate the creation of inventories for textile processes, including textile chemicals. From the LCIA point of view, the answer to the third research question is likewise that the data source selection strategy presented in Paper IV can be used by LCA practitioners who are non-experts in chemistry to reduce uncertainty in calculating new characterisation factors. The nomenclature creates transparency in the modelled LCIs, and increases their usability as LCI data in screening LCAs of textile products.

Although only textile products and textile chemicals are discussed, several of the findings are potentially applicable also to other product areas and impact categories.

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Appendix 1 Swedish consumption statistics linked to the archetype garments

CN code	Description	Consumption in Sweden 2012 (ton)	Archetype garment
6101	Men's or boys' overcoats, car coats, capes, cloaks, anoraks (including ski jackets), windcheaters, wind-jackets and similar articles, knitted or crocheted, other than those of heading 6103:	320	dress
6102	Women's or girls' overcoats, car coats, capes, cloaks, anoraks (including ski jackets), windcheaters, wind-jackets and similar articles, knitted or crocheted, other than those of heading 6104:	939	dress
6103	Men's or boys' suits, ensembles, jackets, blazers, trousers, bib and brace overalls, breeches and shorts (other than swimwear), knitted or crocheted:	1036	jeans
6104	Women's or girls' suits, ensembles, jackets, blazers, dresses, skirts, divided skirts, trousers, bib and brace overalls, breeches and shorts (other than swimwear), knitted or crocheted:	5234	jeans
6105	Men's or boys' shirts, knitted or crocheted:	1079	T-shirt
6106	Women's or girls' blouses, shirts and shirt-blouses, knitted or crocheted:	926	dress
6107	Men's or boys' underpants, briefs, nightshirts, pyjamas, bathrobes, dressing gowns and similar articles, knitted or crocheted:	1996	T-shirt
6108	Women's or girls' slips, petticoats, briefs, panties, nightdresses, pyjamas, négligés, bathrobes, dressing gowns and similar articles, knitted or crocheted:	2220	T-shirt
6109	T-shirts, singlets and other vests, knitted or crocheted:	10441	T-shirt
6110	Jerseys, pullovers, cardigans, waistcoats and similar articles, knitted or crocheted:	10672	dress
6111	Babies' garments and clothing accessories, knitted or crocheted:	1573	T-shirt
6112	Tracksuits, ski suits and swimwear, knitted or crocheted:	689	T-shirt
6113	Garments, made up of knitted or crocheted fabrics of heading 5903, 5906 or 5907:	229	jacket
6114	Other garments, knitted or crocheted:	948	T-shirt
6115	Pantyhose, tights, stockings, socks and other hosiery, including graduated compression hosiery (for example, stockings for varicose veins) and footwear without applied soles, knitted or crocheted:	5567	dress
6116	Gloves, mittens and mitts, knitted or crocheted:	1525	dress
6117	Other made-up clothing accessories, knitted or crocheted; knitted or crocheted parts of garments or of clothing accessories:	726	T-shirt
6201	Men's or boys' overcoats, car coats, capes, cloaks, anoraks (including ski jackets), windcheaters, wind-jackets and similar articles, other than those of heading 6203:	1874	jacket

CN code	Description	Consumption in Sweden 2012 (ton)	Archetype garment
6202	Women's or girls' overcoats, car coats, capes, cloaks, anoraks (including ski jackets), windcheaters, wind-jackets and similar articles, other than those of heading 6204:	2960	jacket
6203	Men's or boys' suits, ensembles, jackets, blazers, trousers, bib and brace overalls, breeches and shorts (other than swimwear):	9489	jeans
6204	Women's or girls' suits, ensembles, jackets, blazers, dresses, skirts, divided skirts, trousers, bib and brace overalls, breeches and shorts (other than swimwear):	10023	jacket
6205	Men's or boys' shirts:	2642	uniform
6206	Women's or girls' blouses, shirts and shirt-blouses:	2012	uniform
6207	Men's or boys' singlets and other vests, underpants, briefs, nightshirts, pyjamas, bathrobes, dressing gowns and similar articles:	403	uniform
6208	Women's or girls' singlets and other vests, slips, petticoats, briefs, panties, nightdresses, pyjamas, négligés, bathrobes, dressing gowns and similar articles:	547	uniform
6209	Babies' garments and clothing accessories:	379	jeans
6210	Garments, made up of fabrics of heading 5602, 5603, 5903, 5906 or 5907:	3173	jacket
6211	Tracksuits, ski suits and swimwear; other garments:	1703	jacket
6212	Brassières, girdles, corsets, braces, suspenders, garters and similar articles and parts thereof, whether or not knitted or crocheted:	976	jacket
6213	Handkerchiefs:	15	dress
6214	Shawls, scarves, mufflers, mantillas, veils and the like:	536	dress
6215	Ties, bow ties and cravats:	75	jacket
6216	Gloves, mittens and mitts	376	jacket
6217	Other made-up clothing accessories; parts of garments or of clothing accessories, other than those of heading 6212:	129	jacket