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Making Fashion Sustainable The Role of Designers

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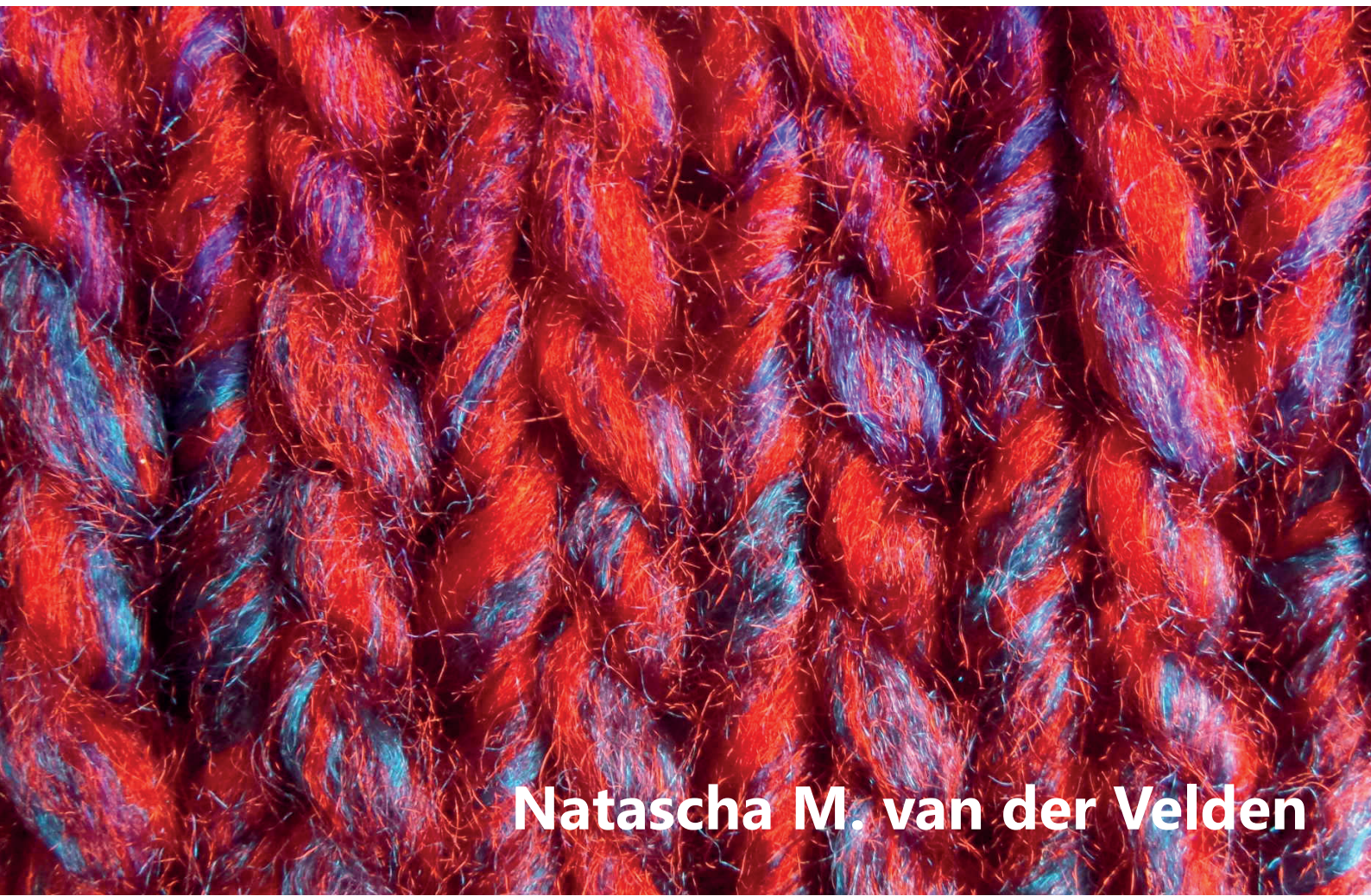
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Making Fashion Sustainable

The Role of Designers



Natascha M. van der Velden

Making Fashion Sustainable

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The Role of Designers

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus prof.ir. K.C.A.M. Luyben,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen op
maandag 5 december 2016 om 10:00 uur

door

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Dr.ir. J.G. Vogtländer of Delft University of Technology has contributed greatly to the preparation of this dissertation.

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The photo of the knit, made by Natascha van der Velden, refers to the finding that clothing made by means of knitting with thick artificial yarn comes out best; based on the life cycle assessment as described in this thesis. The design of the hand-drawn whiteboard was made by Kirsten Lussenburg.

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Making Fashion Sustainable

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The Role of Designers

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Preface

This thesis sprang from my lifelong fascination for fashion and textiles. From the moment I was able to hold a needle, I made outfits for my Monchhichi and Barbies; as soon as I could handle a sewing machine, I made clothing for myself and others.

It still intrigues me how one can create a 3D modelled piece of clothing from flat fabric, or knit a complete garment from one thread. I can still remember the excitement I felt when I visited the – long ago dismantled – Enka viscose manufacturing plant in Enschede and several other textile factories. I was – and still am – fascinated by the long rows of machines and workers making beautiful textile materials and products. The same goes for the upcoming new technologies to create apparels (such as 3D printing and laser cutting); and new (smart) materials (for example, bio-based filaments and conductive polymers) and the ways (young) designers play with these. Making a piece of clothing has always been a subtle, almost ungraspable interplay between the creator, the material, the maker and the wearer. Likewise, I am intrigued by the meanings of fashion for people, its history and the cultures that surround it, and the way the fashion industry operates and has influence.

When someone is asked for the most important products in life, garments are rarely those first mentioned. But when stepping out in the morning for work or school, you might forget your mobile phone or the keys to your house, or a book you possibly need for a course that day. This might seem, at that moment, to be a big problem, but they are problems that can be overcome. When you forget *your clothing*, however, you face real problems! You will get cold (or too warm in hot climates) and people will stare at you. So, are not your garments the most important products in your possession? It is also interesting that when I discuss my research topic – under the broader heading *sustainable fashion* – it always provokes a reaction. Fashion and sustainability affect everybody and everyone has an opinion about it. It is rewarding to notice your research topic has relevance, is (somehow) understood and has a strong connection with people in their daily life. This latter aspect might also stem from the fact that fashion and identity are so closely linked.

My professional career in fashion began with sewing for textile designers and within fashion ateliers. The rise of the sustainability movement presented the opportunity to include the topic in my MSc graduation project undertaken at the Delft University of Technology (TU Delft). The assessment of environmental aspects requires in-depth knowledge about the processes behind the sector and its products. Through both this work and study, it has become clear to me that the viewpoint of an industrial design engineer has valuable potential for the fashion industry. Following my graduation, I started working as a product manager in a fashion company and discovered that sustainability in real world fashion was not, at that time, an issue. This was in the middle of the 1990's, the world economy was recovering from crisis and the internet bubble had begun to grow. It was also the time when *fast fashion* came into being.

My fascination for textile products, the system and the industry, in combination with a hunger for knowledge about the facts behind the sustainability of fashion, are the main reasons for this project. This thesis is the result of a search for a more sustainable fashion industry; a need to answer questions about conscience; and about responsible fashion designers living in the 21st century. I hope to inspire all actors in the fashion industry to create everyday clothes, which are sustainable and foster self-empowerment – of the designers, the wearers and the makers – now and in the future ahead.

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And last but not least, my family and friends, especially my parents and Frank, Madelief and Fleur. Thank you for being there!

Het kind en ik

Ik zou een dag uit vissen,
ik voelde mij moedeloos.
Ik maakte tussen de lissen
met de hand een wak in het kroos.

Er steeg licht op van beneden
uit de zwarte spiegelgrond.
Ik zag een tuin onbetreden
en een kind dat daar stond.

Het stond aan zijn schrijftafel
te schrijven op een lei.
Het woord onder de griffel
herkende ik, was van mij.

Maar toen heeft het geschreven,
zonder haast en zonder schroom,
al wat ik van mijn leven
nog ooit te schrijven droom.

En telkens als ik even
knikte dat ik het wist,
liet hij het water beven
en het werd uitgewist.

Uit: Nieuwe Gedichten, 1934. Martinus Nijhof (1894-1953)

Abstract in English

This thesis looks at sustainable fashion from the viewpoint of the designer and seeks the answer to the central research question: **How can designers contribute to a cleaner and more sustainable fashion production system?**

The goal of the research presented in this thesis is to inform fashion designers (and other stakeholders in the fashion industry) about what they can do to integrate sustainability in their designs by taking into account life cycle assessment study results.

'Fashion' in this thesis refers to 'the clothing that people wear' (inspired by Breuer, 2015, p.34).

To structure the research, the underlying research questions, the results and the conclusions are divided into *metrics* related (i); *production process* related (ii) and *communication* related (iii).

This thesis consists of two parts: (I) the '*Chapeau*', which describes the introduction, the methods, a synopsis of the research results, the discussion, conclusions and recommendations, and (II) the '*Publications*', presenting the six underlying papers, accomplished through an exhibition in the annex.

The introduction section of this thesis shows, that the current fashion system is unsustainable. The problems, which arise from this expanding industry, are twofold: it is polluting and anti-social. The worldwide textile and apparel sector results in material depletion, toxic emissions and social(economic) exploitation.

The first chapter of the Chapeau highlights the insight that designers may be identified as potential actors who can contribute to the transition towards a more sustainable fashion industry, but they lack the right information and practical, open-source, reliable data and tools to provide clear and well-grounded insights into the consequences of design based decisions. This section also introduces the central research question¹, as well as the three underlying research questions², and discusses the scope and delimitations of the research.

The second chapter presents the main methods of the research ('action research and reflective practice'; 'ecodesign and the life cycle design strategies wheel' and 'life cycle assessment and ecocosts'), and shows the relationship between these methods, the research questions and the publications. It forms the prelude to the main approach, which is qualitatively oriented and based on life cycle assessment (LCA) and the (s-)ecocosts method.

¹ Central research question: How can designers contribute to a cleaner and more sustainable fashion production system?

² Research question 1 (RQ 1, metrics related): What are the current flaws in LCAs on textiles and clothing products and what can be done about these?

RQ 2 (production process related): Which innovative technologies and design approaches hold promising contributions for cleaner textile production and a sustainable fashion industry?

RQ 3 (communication related): How can designers (and other stakeholders, such as companies, policy makers, consumers and researchers) be best guided to make well-considered decisions for sustainable clothing products?

The third chapter summarises the results from the publications, ranked under the aforementioned three underlying research questions. The research highlights three flaws in LCA studies of the past:

- (i) the non-existence of yarn count specification in LCA calculations, since it has a major influence on production energy;
- (ii) the exaggeration of the environmental burden of machine washing in the use-phase;
- (iii) the incorrect method of handling carbon sequestration in LCA (to include in LCAs of bio-based textiles).

Furthermore, the research identifies the textile manufacturing stage (fibre production, yarn spinning and weaving) as environmental hotspots, and the garment production phase as the phase with the highest socio-economic costs.

The research on smart textiles reveals that the extra environmental burden of it is worrisome. It can be avoided through careful design, however. The research on 3D printing, digital design and local manufacturing reveals that the environmental burden of these techniques is no less than the impact of 'conventional' methods; however, introduction to a wider audience might have a positive effect on the life span of clothing (since it is tailor-made), as well as a positive effect on the social aspects of the production system.

The fourth chapter of the Chapeau indicates the related discussion points; ranging from the limitations of the numerical approach of the research, to the restricted influence of the designer in the contemporary fashion system. The discussion includes the issue of the responsibility of the designer – to inform their supervisors about the sustainability impacts of the designs – versus the responsibility of the company management – to adhere to corporate social responsibility and to determine a fair price policy.

The evaluation at the end of the fourth chapter examines a combination of the action research and reflective practice methods with the article-based approach, concluding that this is a valuable method of research for this subject area. Furthermore, the inclusion of the social aspect in this PhD was a challenge.

The fifth chapter presents the conclusions of the research, based on the three research questions, underlying the central research theme.

The chapter begins with the conclusion that the metrics related publications have a threefold contribution to the development of life cycle sustainability assessment (LCSA), namely:

- (i) an up-to-date LCA benchmark on textile products from different materials;
- (ii) a solution for the carbon sequestration issue in LCA;
- (iii) the development of a method for quantification of the social impact.

Important conclusions in this context are, among others, that garments made from cotton and wool have a less sustainable footprint than clothing made from man-made fibres, and that the energy use for the fabric manufacturing process, 'knitting', has a factor 20 times lower than the energy needed for 'weaving'.

The production process-related conclusions highlight that additive manufacturing (AM), with or without the combination of co-creation and local production, could be beneficial for a sustainable transformation, but that the right combination of material, structure and process is crucial for success. Furthermore, the research demonstrates that ecodesign improves the environmental performance of

smart textiles and that, by means of the ecocosts method, the environmental gain of redesigns can be mapped out.

The communication related conclusions, in the context of the practice based orientation of this research, refer to the communication between LCA-researchers (on textiles) and (fashion) designers. Firstly, it is concluded that this research positively supports the hypothesis that the unsustainable fashion industry can be transformed into a more sustainable industry by means of providing fashion designers with the right information so they can implement the results of scientific LCA research in fashion design practice.

Secondly, the communication related research question leads to the suggestion that, as long as the validity of existing tools for sustainable fashion design remain questionable, and scientifically sound and appealing ecodesign related metrics are still under development, an intermediate person must take position between the LCA-expert and the designer. This new stakeholder, the 'tranS-LCA-tor' could guide the designer with practical and directly implementable suggestions for sustainable fashion design, based on scientific results from research by LCA-experts.

In line with the above suggestion, the fifth chapter ends with a concise list of answers to the above central research question and calls upon the designer to:

- (i) make well-considered choices for materials and production processes;
- (ii) to learn about life cycle thinking and ecodesign;
- (iii) to carefully consider a company's sustainability policy before accepting work with them.

Chapter six of the Chapeau examines the recommendations for stakeholders other than designers, including research recommendations, and pays special attention to the future activities of the tranS-LCA-tor.

According to a famous quote of fashion designer Coco Chanel (1883-1971), fashion is all around us. Chanel once said that: "Fashion is not something that exists in dresses only. Fashion is in the sky, in the street, fashion has to do with ideas, the way we live, what is happening."

In line with this quote and the research described in this thesis, the ultimate challenge for designers is to make *sustainable* fashion 'a way of living', by means of creating 'Life Cycle Clothing', which enhances the self-empowerment of the designer, the maker, and the wearer. Therefore, the author of this thesis calls on the designer to take up a different role; to become a trendsetter for sustainable fashion.

Abstract in Dutch - Samenvatting in het Nederlands

Dit proefschrift benadert verantwoorde mode vanuit de visie van de ontwerper en zoekt naar het antwoord op de centrale onderzoeksvraag: **Hoe kunnen ontwerpers bijdragen aan een schoner en duurzamer modeproductiesysteem?**

Het doel van het onderzoek dat in dit proefschrift wordt gepresenteerd, is modeontwerpers (en andere belanghebbenden in de mode-industrie) informeren over wat zij, door rekening te houden met de resultaten van levenscyclusanalysestudies, kunnen doen om duurzaamheid te integreren in hun ontwerp.

In dit proefschrift wordt 'mode' gedefinieerd als 'de kleding die men draagt' (geïnspireerd door Breurer, 2015, p.34).

Ten behoeve van de structuur van het onderzoek is een verdeling gemaakt van de onderliggende onderzoeksvragen, de resultaten en de conclusies, in *metriekgerelateerd* (i), *productieprocesgerelateerd* (ii) en *communicatiegerelateerd* (iii).

Dit proefschrift bestaat uit twee delen: (I) het '*Chapeau*', met daarin de introductie, de methoden, een synopsis van de onderzoeksresultaten, de discussie, conclusies en aanbevelingen, en (II) de '*Publications*' waarin de zes onderliggende artikelen worden gepresenteerd, aangevuld met een tentoonstelling in de annex.

De introductie van dit proefschrift laat zien dat het huidige modesysteem niet duurzaam is. De problemen die hierdoor ontstaan zijn tweeledig: deze groeiende industrie is vervuilend en antisociaal. De wereldwijde kledingindustrie leidt tot materiaaluitputting, toxische emissies en sociale en sociaal-economische uitbuiting.

Het eerste hoofdstuk van het Chapeau concludeert dat ontwerpers gezien kunnen worden als potentiële actoren die kunnen bijdragen aan de transitie naar een meer duurzame mode-industrie. Echter, het ontbreekt hen aan de juiste informatie en praktische, open toegankelijke, betrouwbare data en instrumenten die heldere en goed onderbouwde inzichten kunnen geven in de gevolgen van ontwerpbeslissingen. Dit hoofdstuk introduceert eveneens de centrale onderzoeksvraag³, als ook de drie onderliggende onderzoeksvragen⁴, en beschrijft de reikwijdte en de afbakening van het onderzoek.

³ Centrale onderzoeksvraag: Hoe kunnen ontwerpers bijdragen aan een schoner en duurzamer modeproductiesysteem?

⁴ Onderzoeksvraag 1 (RQ 1, metriekgerelateerd): Wat zijn de tekortkomingen in de huidige LCA's van textiel en kleding en wat kan hieraan gedaan worden?

RQ 2 (productieprocesgerelateerd): Welke innovatieve technologieën en ontwerpbenaderingen kunnen leiden tot schonere manieren van kledingproductie en een duurzame mode-industrie?

RQ 3 (communicatiegerelateerd): Hoe kunnen ontwerpers (en andere belanghebbenden, zoals bedrijven, politici, consumenten en onderzoekers) het beste begeleid worden zodat zij weloverwogen beslissingen nemen bij het ontwerpen van duurzame kleding?

Het tweede hoofdstuk presenteert de belangrijkste onderzoeksmethoden ('*action research* en '*reflective practice*;', '*ecodesign* en het '*life cycle design strategies wheel*' en '*life cycle assessment* en '*ecocosts*') en geeft aan wat de relatie is tussen deze methoden, de onderzoeksvragen en de publicaties. Dit overzicht vormt de opmaat tot de belangrijkste aanpak die kwalitatief georiënteerd is en gebaseerd is op de levenscyclusanalyse (LCA) en de (s-)ecokosten methode.

Het derde hoofdstuk omvat een samenvatting van de resultaten uit de publicaties, gerangschikt naar de eerdergenoemde drie onderliggende onderzoeksvragen. Het onderzoek geeft drie gebreken aan in LCA-studies uit het verleden:

- (i) de garendikte specificatie in LCA-berekeningen is niet meegenomen, wat van invloed is op de benodigde energie voor productie;
- (ii) de overschatting van milieuvervuiling door de wasmachine in de gebruiksfase;
- (iii) de incorrecte wijze waarop opslag van CO₂ in de LCA wordt geïntegreerd (om op te nemen in LCAs van bio-gebaseerd textiel).

Daarnaast wijst het onderzoek de textielfabricagefase (vezelproductie, garensprengen en weven) aan als meest milieuvervuilend en de kledingproductiefase als fase met de hoogste socio-economische kosten (*hotspots*).

Het onderzoek over slim textiel laat zien dat de extra milieulast hiervan zorgwekkend is, maar dat dit door middel van een doordacht ontwerp vermeden kan worden. Het onderzoek naar 3D-printen, digitaal ontwerpen en lokale productie toont aan dat de milieu-impact van deze technieken niet minder is dan de impact van conventionele methoden, maar dat een bredere toepassing ervan een positief effect kan hebben op de levensduur van kleding (omdat het op maat is gemaakt) en op de sociale aspecten van het productiesysteem.

Het vierde hoofdstuk van het Chapeau behandelt de discussie, uiteenlopend van de beperkingen van de numerieke aanpak van het onderzoek tot de beperkte invloed van de ontwerper op het huidige modesysteem. Daarnaast behandelt de discussie de verantwoordelijkheid van de ontwerper - om hun leidinggevend te informeren over de duurzaamheidsimpact van hun ontwerp - versus de verantwoordelijkheid van het bedrijfsmanagement - om maatschappelijk verantwoord te ondernemen en een eerlijk prijsbeleid te hanteren.

De evaluatie aan het einde van dit hoofdstuk concludeert dat de combinatie van de methoden *action research* en *reflective practice* een waardevolle aanpak is voor dit onderzoeksgebied. Bovendien geeft de evaluatie aan dat de integratie van het sociale aspect in LCA een grote uitdaging is.

Het vijfde hoofdstuk presenteert de conclusies van het onderzoek gebaseerd op de drie onderzoeksvragen die onderliggend zijn aan het centrale thema.

Het hoofdstuk begint met de conclusie dat de kwantitatiefgerelateerde publicaties een drievoudige bijdrage leveren aan de ontwikkeling van de levenscyclusduurzaamheidsanalyse (*lifecycle sustainability assessment*, LCSA), namelijk:

- (i) een bijdetijdse LCA-vergelijking van textiele producten van diverse materialen;
- (ii) een oplossing voor het onderwerp 'opslag van CO₂ in LCA';
- (iii) de ontwikkeling van een methode voor de kwantificering van sociale impact.

Belangrijke conclusies in deze context zijn onder andere dat kleding gemaakt van katoen en wol een minder milieuvriendelijke voetafdruk heeft dan kleding gemaakt van kunstvezel.

Ook het energieverbruik voor het fabricageproces 'breien' is een factor twintig lager dan de energie die benodigd is voor 'weven'.

De productieprocesgerelateerde conclusies geven aan dat *additive manufacturing* (AM), eventueel in combinatie met co-creatie en lokale productie, de duurzame transformatie zou kunnen bevorderen, maar dat een juiste combinatie van materiaal, structuur en proces cruciaal is voor succes.

Daarnaast toont het onderzoek aan dat ecodesign de milieuprestatie van slim textiel verbetert en dat door middel van de eco-kostenmethode de duurzaamheidswinst van alternatieve ontwerpen in kaart kan worden gebracht.

De communicatiegerelateerde conclusies, terwijl de praktisch gebaseerde aanpak van dit onderzoek in acht wordt genomen, verwijzen naar de communicatie tussen LCA-onderzoekers (op kleding- en textielgebied) en (mode)ontwerpers.

De allereerste conclusie (onder deze noemer) is dat het onderzoek de onderliggende hypothese in positieve zin ondersteunt: de niet-duurzame mode-industrie kan getransformeerd worden tot een duurzamere mode-industrie door modeontwerpers te voorzien van de juiste informatie, zodat zij de resultaten van wetenschappelijk LCA-onderzoek kunnen implementeren in de praktijk van modeontwerp.

Ten tweede leidt de communicatiegerelateerde onderzoeksvraag tot de conclusie dat een intermediair nodig is tussen de LCA-expert en de ontwerper, zolang de validiteit van bestaande instrumenten (*tools*) onzeker blijft en de wetenschappelijke en aantrekkelijke ecodesigngerelateerde berekeningsmethodiek nog in ontwikkeling is. Deze nieuwe belanghebbende, de '*tranS-LCA-tor*', kan de ontwerper begeleiden door praktische en direct implementeerbare suggesties te geven voor duurzame mode die gebaseerd zijn op wetenschappelijke resultaten voortkomend uit onderzoek van LCA-experts.

In lijn met bovenstaande suggestie eindigt het vijfde hoofdstuk met een overzichtelijke lijst van antwoorden op de gepresenteerde onderzoeksvraag aan het begin van deze samenvatting en roept de designer op om:

- (i) weloverwogen keuzes te maken voor materialen en productieprocessen;
- (ii) het zogenaamde levenscyclusdenken en ecodesign toe te leren passen;
- (iii) een goede evaluatie te maken van het duurzaamheidsbeleid van het bedrijf waar werk voor wordt verricht.

Hoofdstuk zes van het Chapeau geeft aanbevelingen voor belanghebbenden, anders dan ontwerpers, inclusief suggesties voor verder onderzoek. Tevens vraagt dit hoofdstuk extra aandacht voor de toekomstige activiteiten van de tranS-LCA-tor.

Volgens een beroemde uitspraak van modeontwerper Coco Chanel (1883-1971) is mode alomtegenwoordig. Chanel heeft eens gezegd: "Mode is niet iets dat alleen in jurken bestaat. Mode is in de lucht, op straat en heeft te maken met ideeën, met de manier waarop wij leven, met wat er gebeurt."

In lijn met deze uitspraak en het onderzoek zoals beschreven in dit proefschrift is de ultieme uitdaging voor modeontwerpers om *verantwoorde* mode tot een 'manier van leven' te maken. Dit kan de ontwerper doen door het creëren van 'Life Cycle Clothing', die het autonoom ontwikkelvermogen van de ontwerper, de maker en de drager vergroot. Daarom roept de auteur van dit proefschrift de ontwerper op om een andere rol aan te nemen en om een *trendsetter* te worden voor duurzame mode.

List of publications in Part II

Van der Velden, N. M., Patel, M. K., & Vogtländer, J. G. (2014). LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane. *The International Journal of Life Cycle Assessment*, 19(2), 331-356

Vogtländer, J. G., van der Velden, N. M., & van der Lugt, P. (2014). Carbon sequestration in LCA, a proposal for a new approach based on the global carbon cycle; cases on wood and on bamboo. *The International Journal of Life Cycle Assessment*, 19(1), 13-23

Van der Velden, N.M. & Vogtländer, J. G. (2016). Monetisation of external socio-economic costs of industrial production: A Social-LCA-based case of clothing production. *Journal of Cleaner Production* (under review)

Lussenburg, K., van der Velden, N. M., Doubrovski, E. L., Geraedts, J. M. P., & Karana, E. (2014, October). Designing with 3D Printed Textiles: A case study of Material Driven Design. In: *iCAT 2014: Proceedings of the 5th International Conference on Additive Technologies*, Vienna, Austria, 16-17 October 2014. *Interesansa-zavod*, p. 74-81

Stam, C. J., van der Velden, N. M., Rubio, G., & Verlinden, J. C. (2014, October). Redefining the role of designers within an urban community using digital design and localised manufacturing of wearables. In: *iCAT 2014: Proceedings of the 5th International Conference on Additive Technologies*, Vienna, Austria, 16-17 October 2014, *Interesansa-zavod*. p. 82-89

Van der Velden, N. M., Kuusk, K., & Köhler, A. R. (2015). Life cycle assessment and ecodesign of smart textiles: The importance of material selection demonstrated through e-textile product redesign. *Materials & Design*, 84, 313-324

Appended contribution in Annex I

Exhibition Fair Made Fashion Lab. Life Cycle Clothing. With IDE MSc graduate Kirsten Lussenburg. <http://www.humanityhouse.org/tentoonstellingen-item/natascha-van-der-velden/>, Humanity House, The Hague, April - December 2014

Abbreviations

AM	Additive manufacturing
BSc	Bachelor of science
C	Chapter
CCC	Clean Clothes Campaign
CO ₂	Carbon dioxide
CRQ	Central research question
CSR	Corporate social responsibility
D4S	Design for sustainability
DE	Design engineering
DfS	Design for sustainability
DIY	Do-it-yourself
dtex	Decitex
E-LCA	Environmental life cycle assessment
EOL	End-of-life
EVR	Ecocosts/value ratio
FDM	Fused deposition modelling
IDE	(Faculty of) Industrial design engineering
IPD	Integrated product design
LCA	Life cycle assessment
LCC	Life cycle costing
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LCSA	Life cycle sustainability assessment
LiDS	Life cycle design strategies
MDD	Material driven design
MDM	Multilevel design model
MSc	Master of science
MSP	Material, structure and production process (combination)
NGO	Non-governmental organisation
NL	the Netherlands
P	Publication
PET	Polyester
PhD	Doctor of philosophy
PLA	Polylactic acid
SDDM	Sustainable development design method
SDG	Sustainable development goal
SEC	Socio-economic costs (s-ecocosts)
SKC	Schone Kleren Campagne
S-LCA	Social life cycle assessment
TU Delft	Delft University of Technology
RQ	Research question
RQ P.x	Sub-research question <x>
SMEs	Small and medium sized enterprises

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C.1 Introduction

1.1 Problem background

1.1.1 The textile and fashion industry

"The textile and fashion industry is one of the biggest and oldest industrial sectors in the world" (Niinimäki, 2013, p.14). Textile production and consumption has been growing ever since the Industrial Revolution and at exponential rates over the past decades. Today the output of global fashion and textile production is estimated "... to be more than 30 million tons annually" (ibid.). In 2013, world exports of textiles and clothing rose by 8%, four times higher than the average growth for world exports (2%) and valued at US\$ 766 billion (WTO, 2014). The European Union is the largest importer of clothing, accounting for 38% of world imports in 2013, followed by the United States with 19% (ibid.). In all Western countries, between 90 and 95% of sold garments are imported (Niinimäki, 2013, p.14).

Figure 1 shows the ranking of important garment producing countries according to a recent report of McKinsey (2016). Chief purchasing officers of large European companies such as H&M, Primark and Tesco were asked to rank the top three apparel sourcing countries for the next five years, which, according to McKinsey, leads to the conclusion that China is in decline and Bangladesh remains at the top of the list of future sourcing destinations. McKinsey states that, for the first time in the survey, African nations appear on the list of countries expected to play more important roles in apparel manufacturing.

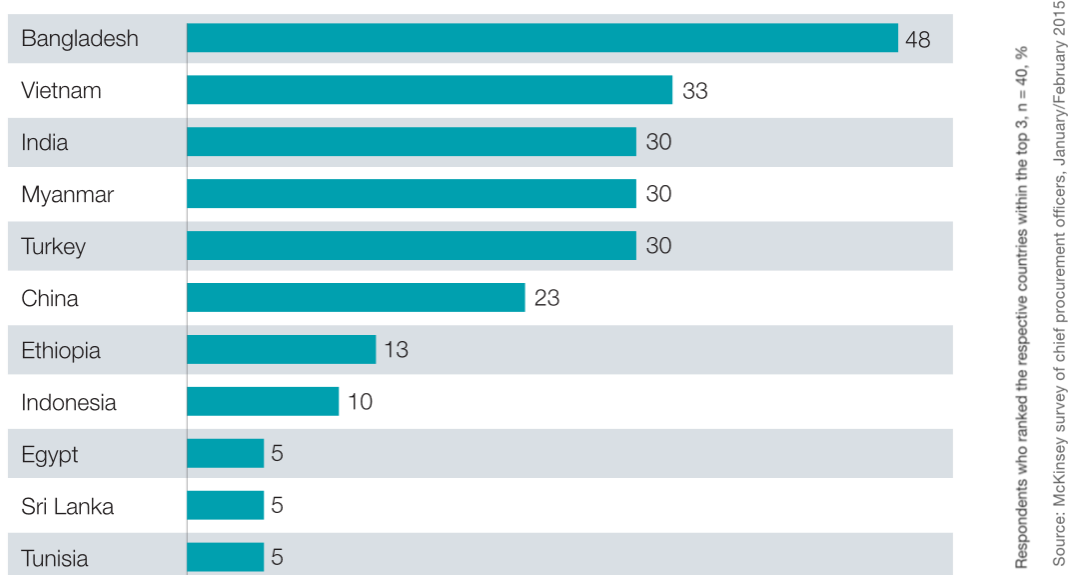


Fig. 1 Important apparel producing countries worldwide 2015-2020

According to an estimation by ILO (2014, p.9-10), in the years 2009-2010 around 22 million people worked in the global clothing and textiles sector. Stotz and Gillian (2015) state that, in 2014, about 60-75 million people were employed in the textile, clothing and footwear sector worldwide; compared to only 20 million people in the year 2000.

"Textiles and clothing production is among the industries that contribute most negatively to environmental and social aspects of sustainability" (Laitala et al. 2015). In fact, the industry was recently ranked second, after oil (Sweeny, 2015). Textile production and consumption combined make up 3% of global CO₂ emissions (Laitala et al. 2015; referring to Madsen et al. 2007 and Carbon Trust, 2011). More specifically, Carbon Trust (2011) calculated that the "global production of clothing results in around 330MtCO₂ being produced annually, which is about 1.2% of global human CO₂ production emissions. In-use emissions from clothing, principally arising from washing and drying, but including ironing and dry-cleaning, cause a further ~530MtCO₂ to be emitted, equivalent to around 2% of global emissions." The *Environmental Impact of Products* study by the European Commission's Joint Research Centre recently identified textile products "... as a priority group, which makes a significant contribution [of 2-10%] to environmental impacts in Europe" (Cordella et al. 2014, p.8). "The analysis highlighted that the volume of clothing, on a weight basis, is almost twice that of household textiles" (ibid. p.9). The average apparent annual consumption of clothes was estimated at 13.5 kg per citizen per year (ibid. p.9).

The ILO (2014) states: "Working conditions in the clothing industry and some industry practices can be particularly challenging for female workers ... Long and unpredictable working hours and safety concerns ..., low wages, weak collective bargaining opportunities and lack of equal pay for work of equal value can make women vulnerable to exploitation inside and outside the workspace." (ibid.) In a recent special report centred on child labour, the Guardian (2015) said that "many of the [170 million] child labourers [worldwide] work within the fashion supply chain, making textiles and garments to satisfy the demand of consumers in Europe, the US, and beyond."

In the recently released *Convenant Duurzame Kleding en Textiel* (SER, 2016), "clothing and textiles" is identified – in a report of KPMG for the Dutch government – as a sector with an "enlarged risk of violation of human rights, environmental norms and animal welfare".

Documentary makers (Van der Keuken, 2015; Morgan, 2015, see Figure 5), NGOs (e.g. Greenpeace, 2016) and journalists (e.g. Laterveer, 2015) have recently reported that the overall⁵ situation in the textiles sector has not yet shown improvement. They express concerns with regards to the ongoing pollution of the environment and continuing social exploitation of workers in the sector, as well as a shift of production to countries with less stringent environmental legislation and a higher prevalence of inequality and no minimum wage.

⁵ Referring to the rough situation, leaving aside many gratifying smaller initiatives, such as the establishment and rise of sustainable fashion brands (e.g. People Tree and Studio YUX), - retailers (e.g. Charly + Mary), - designers (e.g. Rianne de Witte and Monique van Heist), - webshops (e.g. watMooi), - apps (e.g. Talking Green), etc., which are definitely worth a mention also.

As can be seen in Figure 2 (Afcot, 2016), two fibres dominate and are projected to dominate the expanding textiles market: cotton and polyester (Fletcher, 2008 p.6). Cotton and Polyester (staple fibres) are named 'unequal competitors', because (i) global fibre demand is rising and, according to the International Cotton Advisory Committee, (ii) global cotton production is approaching its physical maximum (Afcot, 2016). Therefore, it is expected that the production of polyester fibres will increase in the future and the production of cotton fibres will remain at the same level or slightly decrease (see in Figure 2).

To give an indication of the countries in which cotton and polyester are being produced, Figure 3 (Statista, 2016) shows the leading cotton producing countries worldwide in 2014-2015 (in thousand metric tons) and Figure 4 (Afcot, 2016) presents an overview and projections of the world polyester staple production per country/region (in million metric tons). Figures 3 and 4 demonstrate that China, India and the United States are the largest cotton producing countries and that polyester is mainly produced in China and South and South East Asia.

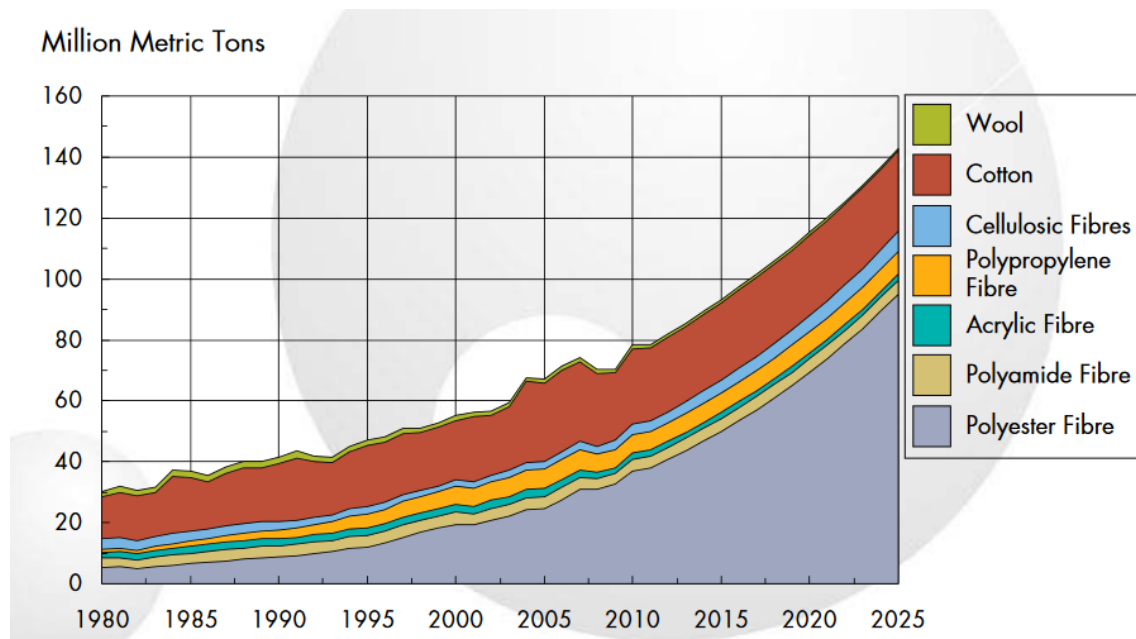


Fig. 2 World fibre production 1980-2025 (Afcot, 2016)

For the fibres presented in Figure 2, the following classifications apply: Wool and Cotton are natural fibres. Cellulosic fibres are half-synthetic, regenerated, and can be ranked under man-made or manufactured fibres. Polypropylene, Acrylic, Polyamide and Polyester fibres are full-synthetic and man-made and manufactured also (Gardetti and Torres, p.4).

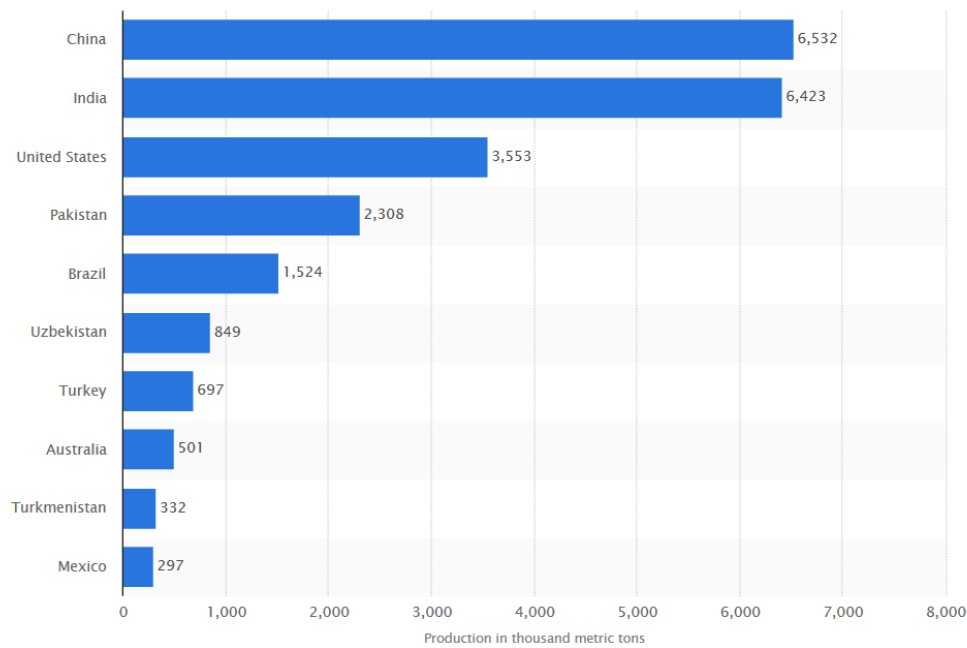


Fig. 3 Leading cotton producing countries worldwide in 2014-2015 (Statista, 2016)

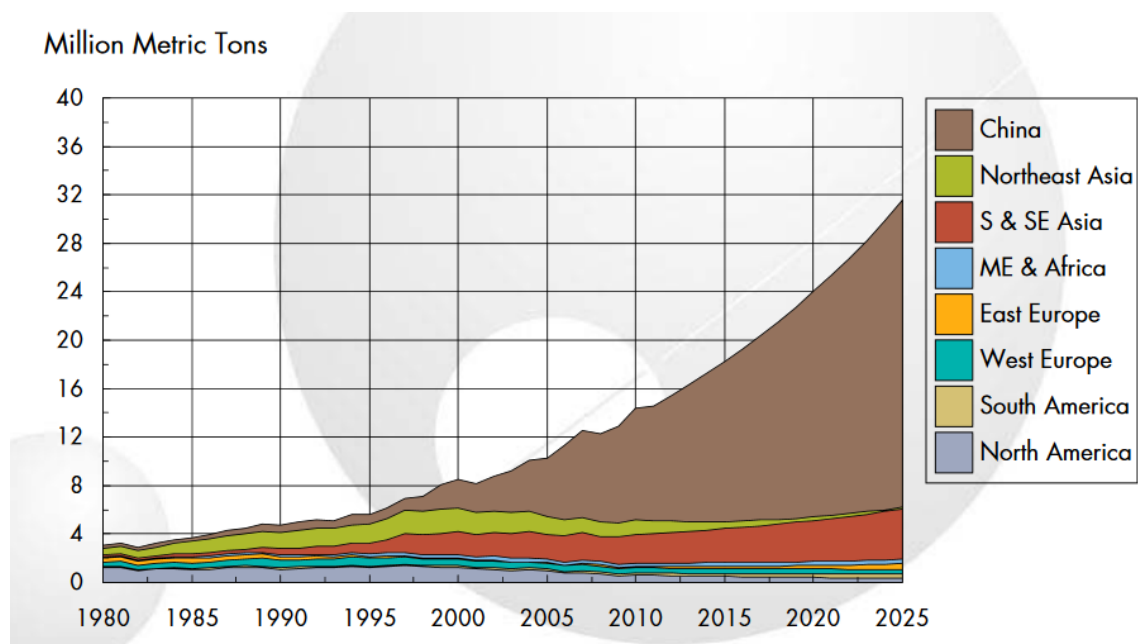


Fig. 4 World polyester staple production 1980-2025 (Afcot, 2016)

By way of a summary of this brief introduction section about the textile industry (including its magnitude, the main feedstock materials and the producing countries) Figure 5 shows a collage of images that represent the problems arising from this industry: social exploitation, toxic emissions and materials depletion.

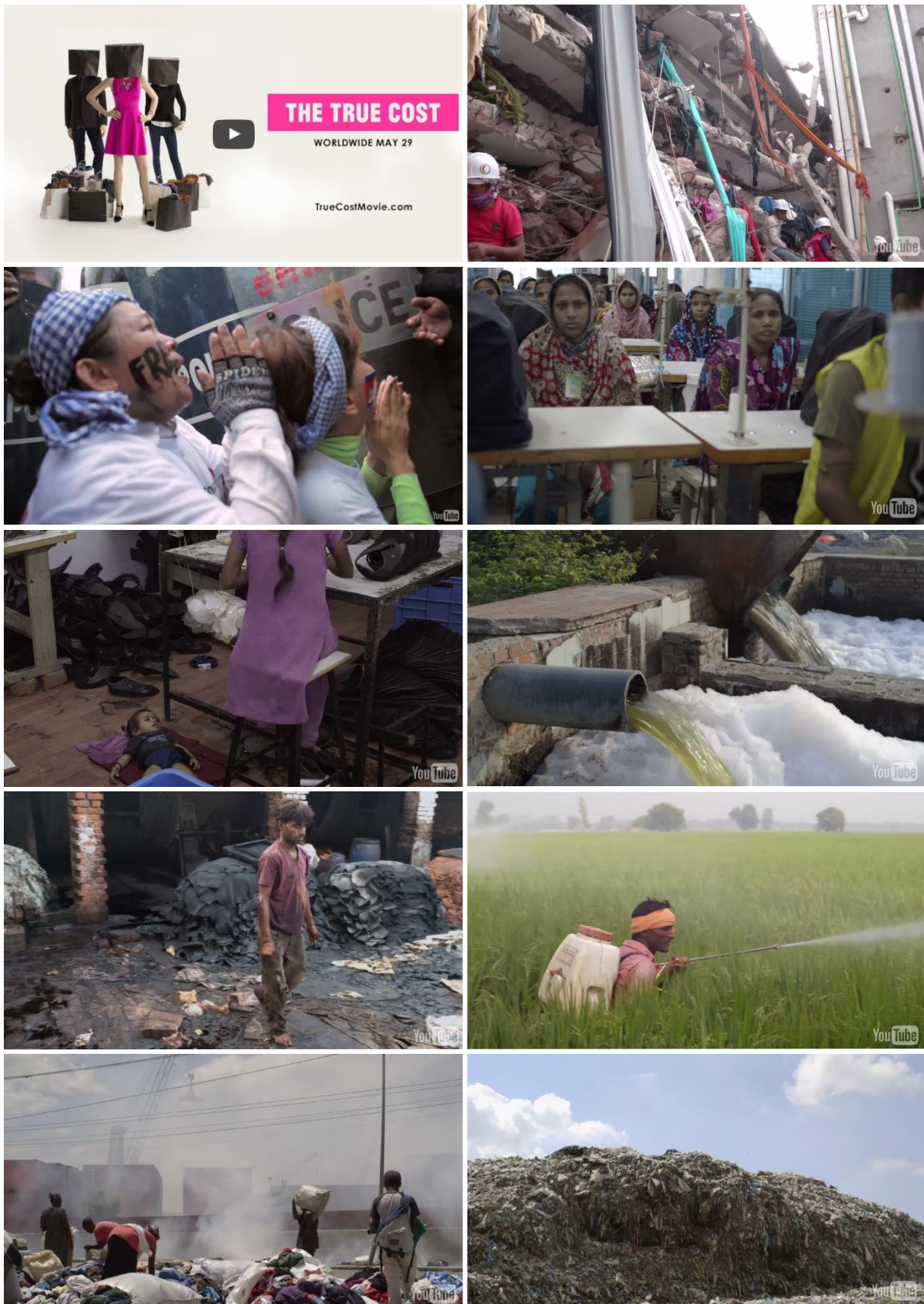


Fig. 5 Stills from the *True Cost Movie* (Morgan, 2015), a documentary film featuring the problems associated with the current textile industry.

1.1.2 A brief historical outline

The fact that the fashion industry is polluting and anti-social has been receiving renewed attention over the past decade, not only from (non-)governmental organisations, consumers and researchers, but also from within the industry itself. This section describes a brief historical outline of the entrance and development of sustainable thinking in the fashion industry.

Probably originating in Germany⁶, the lively debate⁷ about sustainability and fashion started in the early 1990s, and mainly concentrated on the source of the fibre materials used for clothing products (Weller, 2013). The general idea was that sustainable fashion should be made from natural materials, of which, next to synthetic polyester (PET), cotton⁸ has been by the far the most dominant material used. Conventional cotton became known for its polluting character due to the use of large amounts of fertiliser and pesticides during cultivation. Fashion brands (first of all Esprit in 1993, soon after H&M, de Bijenkorf, C&A and H&M) launched *e(co)-collections*, which were made from biological (eco-)cotton (Van der Velden, 1994, p.11).

In the more financially abundant years towards the turn of the century, the debate faded away and *e(co)-clothing* disappeared (Weller, 2013), in favour of *fast fashion*. No information could be found on the moment when exactly the concept of fast fashion was introduced and by whom. Several sources (e.g. Tokatli et al. 2008 and Bhardwaj and Fairhurst, 2010) also refer to 'throwaway' fashion, and name, for example, Burton group's specialty stores Top Man and Top Shop as well as Marks & Spencer and Liz Claiborne as being one of the first, soon followed by Zara, Hennes & Maurits, Mango and New Look. Briggs (2013, p.188) indicates that the roots of 'fast fashion' date back to the 1980s and refers to the pioneering adoption of it by Benetton.

Fast fashion was recently described by Beumer and Koning (2015) as "... the expression of a democratised market ...", which had "... its first and unique manifestation in the Netherlands [and was introduced by Mac & Maggie⁹], eventually leading to shopping districts filled with chains such as Hennes & Mauritz, Zara and Primark. ... Making clothing is hardly present anymore: buying clothing all the more." This line of argument is followed by Farrer (2011, p.20), who describes the current British fashion retail system as "... being driven by a few huge industrial fashion retailers ... [who] have economies of scale and can buy large volumes of clothing at ever lower prices, creating a *churn* of affordable, well designed goods into and out of store, which can be constantly refreshed, so delighting

⁶ Weller (2013) mentions that "ecological clothing appeared on the German market at the end of the 1970s ..." and about "reports and debates on the possible health dangers of clothing in Germany in the 1980s."

⁷ Although Weller (2013) reports about the consumer magazine ÖKO-TEST, which was introduced in 1985 in Germany, according to Gardetti and Torres (2013), only in 1998 did the first books about textiles, fashion and sustainability appear (see: Gardetti and Torres, 2013, p.9-11 for an extensive overview of these books).

⁸ "In the mid-1990s, the production of PET [polyester] fibre exceeded that of cotton [...]; since then, PET has been the most important fibre in the world to this day." (Shen, 2011)

⁹ By citing the description of Frans Ankoné (then stylist at P&C and involved in the initial establishment of Mac & Maggie) who indicates Mac & Maggie as "fast fashion avant la lettre", Köppchen (2014) confirms the finding that Mac & Maggie was one of the first brands to introduce fast fashion - by means of translating ... "designer fashion as shown in Paris and Milan as quickly as possible into affordable, wearable, but highly unique clothes".

the consumer who is ever willing to buy more...". Niinimäki and Hassi (2011, p.1878) likewise ascertain that: "The present system in the textile and clothing industry is based on fast cycles of fashion trends that aim to continuously produce new consumer needs and products. Product lifecycles are shortening, and companies want to substitute their products at an increasing pace¹⁰."

To date, the *fast fashion* concept continues to dominate in Europe and the United States and has been introduced over the past decade in emergent economies in the Middle and Far East.

As a reaction to fast fashion, the concept of 'slow fashion' was introduced (Fletcher, 2008) as "... a way to re-evaluate our relationship with speed ..." (ibid. p.172). This movement adopted the norms and values of socio-cultural well-being (Manzini, 1999); slow design (Fuad-Luke, 2002) and the slow food movement (introduced by "father of the Slow Food Movement" Carlo Petrini (Savaskan, 2013)), but has been commonly misunderstood. In particular, the fashion media misinterpreted the concept "... as a descriptor for products that are in some way less fast" (Fletcher, 2010, p.262). Fletcher (2008; 2010) as well as Niinimäki (2011) describe slow fashion not as the opposite of fast, but as "... a different worldview that names a coherent set of fashion activity that promotes variety and multiplicity of fashion production and consumption and celebrates the pleasure and cultural significance of fashion within biophysical limits" (Fletcher, 2010, p.262). Slow fashion, as Fletcher and Niinimäki describe it, is not about slowing down lifecycles, but about considerably designing clothing products via a multi-layered, diverse, quality-based agenda (Fletcher, 2008, p.174), in which fast and slow fashion might be combined in different production systems with different taxation and labels for these (Niinimäki, 2011, p.142).

The numbers behind the contemporary fashion system and the consequences for the environment were the subject of widespread attention in 2006 with the release of the (almost iconic) report *Well Dressed* (Allwood et al. 2006), made by researchers at Cambridge University. The scientific analysis included predictions of "... the environmental, economic and social consequences of changes in production structure, consumer behaviour, material and process innovations and government influence." The researchers identified the consumer as a central catalyst for change to reduce environmental impact and promote social equity.

During the same period, the industry gradually began to include sustainability assessment in their operations and started to integrate corporate social responsibility (CSR) in supply chain management (Kogg, 2009). Meanwhile, a proliferation of international certifications and labelling arose – varying in the level of sustainability improvement by focussing on the environment, fair trade and/or labour issues – leaving companies, consumers and designers¹¹ in confusion (De Waart et al. 2009, p.54). In 2011, 30 large fashion companies (with members accounting for 60% of global sales) launched a multi-stakeholder alliance (named: *The Sustainable Apparel Coalition*) with the aim to draft a set of sustainability indicators for use across the entire garment industry (Poldner, 2011, p.277).

¹⁰ "The number of collections per year has increased significantly in the past 25 years, with some fashion brands offering up to 20 collections each year." (ILO, 2014, p.1)

¹¹ In this thesis the words "designers" and "fashion designers" are used interchangeably but all refer to the designers of clothing products (see also Section 1.1.3).

The Cradle-to-Cradle¹² (C2C) movement and the Circular Economy¹³ (CE) introduced the body of ideas of thinking in material loops, either in biological or technical cycles, including design for long-lifespan, disassembly and/or recycling. C2C and CE has been inspiring many textile companies and designers worldwide, inciting clothing collection schemes and accelerating the development of textiles made from recycled materials, produced from both chemical (mainly PET-recycling, e.g. Eco-fi) and natural origin (cotton recycling, e.g. saXcelltm).

Simultaneously, the development of modern technology has been stimulating the textile industry (both researchers and designers) to create technologically advanced and complex systems and products. At this moment (at the beginning of 2016) smart textiles and 3D-printed textiles can be found in high regions of their hype cycles. For sustainable textile design these developments evoke increasing concerns (Köhler, 2013) as well as opportunities (Toeters et al. 2013).

Finally, there is one event in recent history that should be part of this brief historical overview about sustainability in the clothing and textiles sector: The collapse of the Rana Plaza (2013) factory in Bangladesh on 24 April 2013, described by the Clean Clothes Campaign as “the worst ever industrial accident to hit the garment industry”. This event raised global attention to the appalling working conditions of many workers in the textiles industry and led to the Accord of Fire and Building Safety in Bangladesh (CCC, 2016).

The review in this introduction argues that in the future a *growing* population of consumers will most probably buy (consume) *more* clothing, which, in turn, will *enlarge* the negative effects on the environment and social well-being of the world population.

1.1.3 Defining the solution space and target group

The preceding brief historical overview of sustainability in the fashion industry leads to the following formulation of four main discussion areas:

- the choice of materials, production chains and fabrication methods (1)
- a fair distribution of money among the workers throughout the chain (2)
- customer behaviour (buying, use- and re-use, cleaning, disposal), waste handling and recycling (3)
- communication of the (un)sustainability of apparel (4)

Furthermore, following the explanation in Section 1.1.2, the following key-actors, who can contribute to a more sustainable fashion industry are identified:

- companies – creating fashion brands, bringing textiles on the market and managing the supply chains (a)
- certification bodies – defining requirements for textile materials and processes (b)

¹² popularized by McDounough and Braungart since 2002 (Pauw, 2015)

¹³ brought under wide attention by the Ellen MacArthur Foundation (2010)

- researchers – contributing to the body of knowledge (c)
- consumers – buying, taking care, cleaning, re-using and disposing of apparel (d)
- policy makers – framing legislation (e)
- non-governmental organisations (NGOs) – exerting influence on several parties (f)

A recent comprehensive Swedish study (Roos et al. 2016) about sustainable development at the level of (national) industry sectors identified the following groups of actors as stakeholders of the Swedish fashion sector: consumers, brands, suppliers, sub-suppliers, authorities, investors, media and NGOs and proposes different interventions relevant to different actors.

There is no evidence within this overview that the *fashion designer* has played any part in the sustainability debate as yet. Not only is the fashion designer not mentioned (at least not as one of the actors who scrambled for a sustainable fashion industry) but the above lists of possible influencers do not specifically describe *the designer* as a leading figure. Also, the Swedish study does not specifically mention designers and/or design interventions (ibid.)¹⁴.

But, is it not the designers who decide how and which products enter the market and via which channels they are manufactured and sold and how they are used and end their life?

From the historical overview (in Section 1.1.2), it can be concluded that fashion designers have not been frontrunners in the debate about sustainability and fashion, nor have they been those to evoke the necessary transition. At the famous catwalks in Paris, Milan and Tokyo, which are an important inspiration source for the fashion industry and the consumers, sustainability has been conspicuous by its absence¹⁵. Furthermore, none of the famous, influential fashion designing laureate are known for the integration of sustainability in their designs¹⁶.

How can it be that, while fashion is generally known for its progressive character and is associated with innovation and change, the average appearance of garments in shops does not differ extensively from what was available 30 years ago (unlike many other products, which have experienced unprecedented transformations due to technology development, e.g. television sets, cars etc.)? And why is information about sustainability hardly present on the shop floor, but often over-represented in online

¹⁴ In another recent publication (Future Fashion Manifesto, 2015), the same research group does address the designer and emphasises that: "Today the designer has a limited role and commonly functions within limited scope of influence. Designers are often limited by their restrictive departmental roles. Most often the designer is missing relevant tools; influence beyond their section, knowledge and insight on their available options to sustainable decisions." The same document advises designers to include strategic design thinking for sustainable fashion design and points out that, by doing so, environmental performance improvement is about 41%.

¹⁵ Leaving aside smaller national (e.g. Ethical Fashion Show Berlin; following up the Ethical Fashion Show Paris after nine editions since 2013) and local (e.g. Fair Fashion Festival Utrecht, Fair Fashion Fest Gent) initiatives, which are less well-known and less influential. Here it should also be noted that a few up and coming Dutch fashion designers (Jef Montes and Maison de Faux of Tessa de Boer and Joris Suk) showcased their commitment to sustainability by denouncing the fashion system in much talked-about performances at the Amsterdam Fashion Week 2016.

¹⁶ Stella McCartney, Vivienne Westwood* and Yohji Yamamoto* might be among the few exceptions that prove the rule.

* also identified by Breuer (2015, p.268)

communication of fashion brands? Focussing on a product level and then examining the broader picture over time, the biggest difference in the industry is that the quality is lower, volume is greater and there is more emphasis on marketing.

Scientific literature in the field of design research claims that designers can play an important role towards sustainable transitions. "It is estimated that the product design and development phase carries approximately 80% or even more of the environmental and social impacts of the product, including the manufacturing, use and disposal phases (Tischner & Charter 2001, 120). In short, decisions made during the design process affect the environmental impact of the product during its whole life cycle." (Niinimäki, 2011, p.26)

Luttrupp and Lagerstedt (2006, Abstract) state: "The designers are said to have the key to sustainable product development through ecodesign." Furthermore, they emphasise that environmentally driven demands must enter into the early phases of design to be included in the specifications (Luttorp, 2006, p.1397-8).

According to Ramani et al. (2010, p.091004-1): "Product design is one of the most important sectors influencing global sustainability, as almost all the products consumed by people are outputs of the product development process. In particular, early design decisions can have a very significant impact on sustainability..."

Furthermore:

"The role of the designer is becoming more varied: part creator, part researcher, part facilitator, part process manager (Atkinson, 2011). Designers are moving beyond designing solely a product but tailoring a range of touch points into designed services and experiences. These approaches are moving beyond 'stuff', and towards inspiring and empowering change. Vuletitch (2010) even refers to designers as *change makers*." (Ballie, 2012)

Although all the actors in the list at the beginning of this section are expected to be very important, the above discussion justifies the decision to address *the designers*¹⁷ as specific target group for the research of this thesis.

Following Vuletitch's line of thought, (fashion) designers might be referred to as '*Change Agents*', because it can be expected that, in the future, designers will increasingly act as interdisciplinary intermediaries, rather than as maker-producers, such as *agents* ('agens' in Dutch) have been doing in chemical processing (of textiles).

Up to this point, the term designer has not been well defined and 'designer' and 'fashion designer' interchangeably used. In this thesis the **designer** is defined as the person who designs clothing products, therefore the term "clothing designer" also applies. For the definitions of clothing and fashion, the reader is referred to Section 1.4.

¹⁷ This choice does not exclude the fact that this thesis could also be of interest to a wider group of readers, including consumers, business managers, consultants or policy makers and other actors in the textile chain, who are particularly addressed in the Recommendations (C.6).

In the MAKE chapter of the book *Shaping Sustainable Fashion*, Gwilt and Rissanen (2011) describe (1) the phases of fashion design and production (ibid. p.60-62); (2) the fashion designer's role (ibid. p.62-63); (3) the fashion design brief (ibid. p.63-64); and (4) point out three key problem areas when encouraging "... the fashion designer to engage with sustainable design practice". According to Gwilt and Rissanen (2011, p.69-70), the latter comprises: (i) understanding sustainable design strategies; (ii) link sustainable strategies with the fashion design and production process; and (iii) apply lifecycle thinking to the fashion design brief. In addition to this, the next section elaborates further on the problems for the designer.

1.1.4 The problem for the designer

While the role of the designer has been changing (with reference to Vuletitch, 2010; Atkinson, 2011 and Ballie, 2012; see the previous section), awareness about sustainability in the fashion sector has been growing over recent years (see Section 1.1.1). A general observation is that designers (and many of their supervisors) are 'wandering and shopping around on the (data) market'¹⁸ but cannot find what they are looking for. In general, designers lack the right data and information (about materials and production processes) to justify their decisions.

Another issue is that designers are not acting alone but are 'just' a part in the whole fashion system. Designers work for fashion companies (stakeholder (a) in the second listing in Section 1.1.3), which can be existing, new, large or small and with their own mission and value proposition drawn up by company management. The 'sustainable fashion designer' has to find its position in a complicated web of interests; in an industry where 'greenwashing'¹⁹ sometimes is used (by the management) to maximise company profits. In this context, Gwilt and Rissanen (2011, p.72) refer to Kawamura (2005), stating that: "The fashion designer in a micro, small or medium size business does not work in isolation, as the creation of the fashion garment is a collective process".

Extra difficulties stem from the fact that many fashion designers (and many other stakeholders from the e-f list in Section 1.1.3) might not be skilled enough to translate (scientific) research results into practice, nor might they be able to judge communication about sustainability issues in the media. Most fashion designers (and other stakeholders) receive secondary education in fashion institutes, sometimes complemented by higher artistic education at art academies or higher academic education in applied universities, but probably have never carried out scientific research. This is a potential problem when addressing complicated sustainable design issues in a complex industry such as that of fashion (Gwilt and Rissanen, 2011, p.13).

¹⁸ Likewise, Poldner (2011, p.291) describes how "... companies are involved in other initiatives [next to the membership of the Sustainable Apparel Coalition] whether through accreditation, membership or as an affiliate. The data shows that they 'shop around' in search of knowledge on how to green their supply chains."

¹⁹ "Greenwashing is disinformation disseminated by an organization so as to present an environmentally responsible public image. –10th edition of the Concise Oxford English Dictionary" (Ramus and Montiel, 2005, p.377)

Niinimäki (2011, p.93) ascertains that “... textile and clothing design is lacking research knowledge on ecodesign and sustainable design issues”. Although many books (e.g. Black, 2008; see also Footnote 7), research (e.g. Spangenberg et al. 2010; Fletcher, 2012; Niinimäki, 2013), concepts (e.g. Nature-Inspired design, De Pauw, 2015; Circular Economy, Ellen MacArthur, 2010) and innovative products (e.g. Van Dongen, 2013; Van Herpen, 2013) have inspired, the specific role of the designer and which *exact* tasks and actions designers can undertake, methods to truly accelerate the transition towards a more sustainable fashion industry have hardly been described or educated so far.

It is important to note that designers not only choose the materials and production processes, but are also often involved in marketing, and have influence in the communication processes of their products to consumers. In continuation, designers, as concept developers, are the (obvious) people to create new and innovative product service systems (Armstrong et al. 2015), combined with or without new (digitalised) production processes, progressing technologies and retail concepts.

Over the years, several instruments for sustainable improvement of the textiles and apparel sector have appeared, of which many are based on LCA methodology:

- tools for textiles and brands benchmarking (Modint Ecotool, 2012; Higg Index, 2012; Made-by Brand Tools & Benchmarks and ModeTracker, 2016; SAC Tools, 2016; TE, 2016);
- toolboxes (Ecolizer, 2016; The TEN, 2016);
- apps for materials comparison (e.g. Nike Making app, 2013);
- software applications (e.g. the sector-specific data module for Textile finishing in GaBi);

It is interesting to note that LCA has gradually been adopted by the fashion industry as a way to measure sustainability impact, but profound LCA analyses of textile chains and methodology development remain in progress. The same applies for the embedding of LCA results in (fashion) design practice.

In 2004 already, Dahlhöff (2004, Table 4, p.19) reported methodological issues in LCAs for textile products, classifying these “... as issues regarding the procedure and the model, respectively.” Dahlhöff identified the most important problems as: (i) “to find inventory data in general”, (ii) “to assess land use for cotton and wool production”, (iii) “to assess emissions of chemicals to the environment”, and (iv) “to assess irrigation water use for cotton cultivation” (ibid. abstract). Furthermore, Dahlhöff reported, “The LCA methodology for the textile sector is particularly difficult owing to the fact that it often includes land use and that the production chain usually includes many parts of the world causing difficulties in local and regional environmental assessment. Moreover, the specific conditions for cotton cultivation are usually not known and vary greatly causing difficulties in assessing environmental impacts on a local scale, such as land or irrigation water use.” Up to now, these problems have not (or have only partially) been solved, as later confirmed by Shen (2011, p.36-37) and Terinte et al. (2014, p.135), who more recently performed in-depth LCA studies on textile materials and processes, leading to many methods, tools and research, suffering from lack of life cycle inventory data, data inconsistency and problems with allocation and carbon sequestration²⁰.

²⁰ Note that this remark does not refer to the quality of the state-of-the art LCAs as performed by the researchers mentioned in the references in this section.

This leaves the designer with many unanswered questions, such as: How to create sustainable textile products and what does a sustainable fashion industry look like? Which materials are sustainable, natural or synthetic or a combination? What is ecodesign in fashion? How can it be implemented? Should recycled materials be used or products recycled, or both? How will digitalisation alter the appearance of clothing products and the roles of designers, consumers and the market? What does the consumer want and how can ideas and knowledge best be communicated? How can a designer have a positive influence over social dynamics in the value chain?

1.2 Problem definition

Section 1.1 introduced the textile and fashion industry and the sustainability problems associated with the production of clothing (i.e. materials depletion, toxic emissions and social exploitation, see Section 1.1.1).

The brief historical outline (Section 1.1.2) highlighted the rising concerns about these issues (in the 1980s and 1990s) and the rise of fast fashion (from the 1980s onward). It can be argued that this movement, including the integration of modern technology, has contributed to the enlargement of the problems.

The discussion of the definition of the solution space and the target group for this research (Section 1.1.3) led to the decision to choose the designer, who could not be appointed as a frontrunner of sustainable fashion, possibly due to an information gap on how to 'practice sustainable fashion design'.

Summarising the previous introduction, the problem definition underlying this research becomes bipartite:

1.

The worldwide textile and apparel sector is unsustainable, from both an environmental point of view as well as a social point of view, ranging from materials depletion and toxic emissions to social exploitation.

2.

Designers are identified as potential actors who can contribute to the transition towards a more sustainable fashion industry, but the right information and practical, open-source, reliable data and tools to provide clear and well-grounded insights in the consequences of design based decisions are not available.

1.3 Research questions

To conclude the introduction (in Section 1.1) and the problem definition (as formulated in Section 1.2) the **central research question (CRQ)** pertaining to this thesis is formulated as:

How can designers contribute to a cleaner and more sustainable fashion production system?

Referring back to the first two discussion areas in Section 1.1.3. ("the choice of materials, production chains and fabrication methods" and "a fair distribution of money among the workers throughout the chain") the **proposition** is that it would prove very helpful to the transformation if designers made better choices for materials, processes and supply chains, from a sustainable perspective.

Furthermore, it can be argued that knowledge about LCA, which forms the basis for many existing instruments for sustainable design (see Section 1.1.4), might help designers to accelerate the transition towards a more sustainable fashion production system. Based on this argument, the underlying **hypothesis** for this research is formulated as follows:

The unsustainable fashion industry can be transformed into a more sustainable industry (as part of the overall fashion system) by means of providing fashion designers the right information, in order that they can implement scientific LCA research and LCA results in fashion design practice. This hypothesis refers back to the fourth discussion area, raised in Section 1.1.3, which is described as "the communication of the (un)sustainability of apparel".

Based on the above considerations, and to further structure the research, the CRQ is divided into three RQs, which can be grouped under three subject headers: (i) metrics related, (ii) production process related and (iii) communication related. These RQs are formulated as follows:

RQ 1 (metrics related)

What are the current flaws in LCAs on textiles and clothing products and what can be done about these?

RQ 2 (production process related)

Which innovative technologies and design approaches hold promising contributions for cleaner textile production and a sustainable fashion industry?

RQ 3 (communication related):

How can designers (and other stakeholders, such as companies, policy makers, consumers and researchers) be best guided to make well-considered decisions for sustainable clothing products?

Since these three RQs are rather broad for one PhD study, further focus on aspects and issues has been determined. Extra convergence, definitions and further limitations are explained in the following section (1.4, Scope and delimitations), Section 2.2 (Research sequence) and Section 3 (Results).

1.4 Scope and delimitations

This research is about the sustainability of clothing products in a fashion context.

This description immediately highlights the three most important notions, namely *sustainability*, *clothing* and *fashion*, which have to be defined to clarify the scope and boundaries of this research.

Sustainability is a broad and impalpable construct. A widely accepted definition, which links 'sustainability' to 'sustainable development', is given in the *Brundtland report* (Brundtland et al. 1987, p.43): "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Directly linked to this definition is 'the triple bottom line' concept, as first formulated by Elkington and Trisoglio (1996): People, Planet and Profit – also named the Triple-P (see Figure 6). According to this concept, in corporate activities, equal weight should be given to all three dimensions.

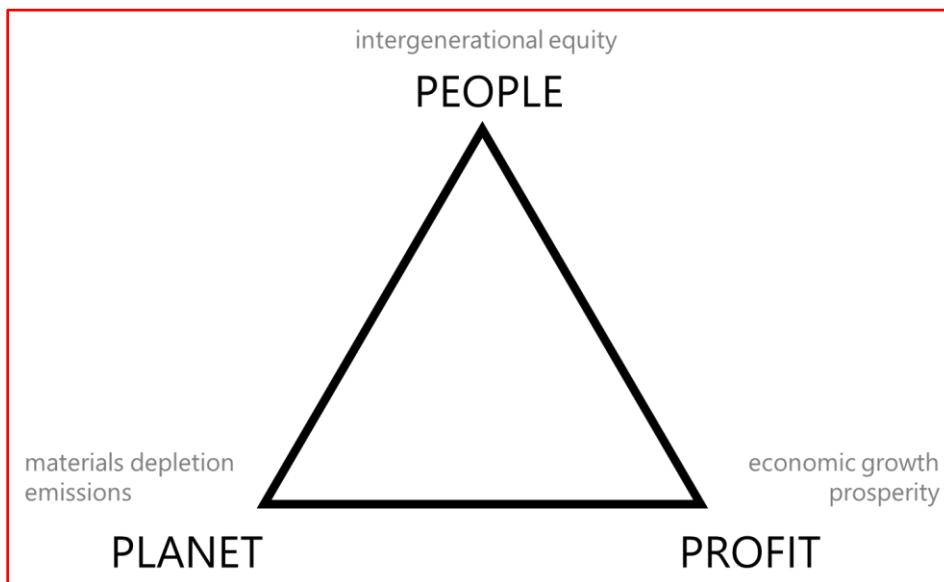


Fig. 6 The Triple-P model

'People' refers to the social aspects of sustainability, or the 'intergenerational equity' as Vogtländer et al. (2013, p.2) describe this dimension, herewith referring to the "...fair global distribution of prosperity, at fair labour conditions..." (ibid. p.3).

'Planet' denotes the ecological consequences for our future environment, caused by materials depletion and emissions as the consequences of human interaction with nature.

'Profit' is linked to the economic 'profitability' of companies, and 'prosperity' of our society with sufficient economic growth to support a better life for poor people.

There are also widely used definitions referring to sustainability that do not include all elements of the triple bottom line. To mention a few related to two of the three elements, economics and ecology (cited from WBCSD, 2005 and WBCSD, 2016):

- ["]As defined by the World Business Council for Sustainable Development (WBCSD), "eco-efficiency is achieved by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and

resource intensity throughout the life cycle to a level at least in line with the Earth's estimated carrying capacity." In short, it is concerned with creating more value with less impact.["]

- ["]The Organisation for Economic Co-operation and Development (OECD) has called eco-efficiency "the efficiency with which ecological resources are used to meet human needs" and defines it as a ratio of an output (the value of products and services produced by a firm, sector, or economy as a whole) divided by the input (the sum of environmental pressures generated by the firm, the sector, or the economy).
- Academic experts and practitioners term eco-efficiency the synthesis of "... economic and environmental efficiency in parallel".
- The European Environment Agency (EEA) defines it as "more welfare from less nature" and says it comes through decoupling resource use and pollutant release from economic development and overall welfare.["]

In a strict sense, the above descriptions are definitions on eco-efficiency – "a management philosophy that encourages business to search for environmental improvements that yield parallel economic benefits" (WBCSD, 2016), and not on sustainability (because the social pillar has been left out). Eco-efficiency refers to the ratio between environmental and economic costs (the comparison of input and output) and as such is useful as a measure to describe sustainability with the objective of improving it. In other words, 'eco-efficiency' is about "...using fewer resources to achieve the same purpose." (Bocken et al. 2016, p.309-310).

Definitions that *do* include social sustainability as well (and by this means cover the three pillars of People Planet Profit) can be found in the aforementioned *Brundtland report* (Brundtland et al. 1987): "What we need now is a new era of economic growth; growth that is forceful and at the same time socially and environmentally sustainable" and, for example, in the UNEP Guidelines for S-LCA of products, in which "the ultimate goal of sustainable development" is described as "human well-being, contributing to the needs of current and future generations." (UNEP/SETAC, 2009, p.16)

In this document, the concept of sustainable development is linked to sustainable production and consumption (and integrates environmental, economic and social dimensions) and mentions the relationship with the "social responsibility of organisations and the objective to improve social and environmental performances along with sustained economic profitability – all in the perspective to contribute notably to greater human well-being." (ibid. p.5)

Furthermore, the construct and effects of 'PPP-thinking' and the definitions derived from this have been criticised because the focus is more on "... the process of using up and on the materiality of consumption ..." (Ehrenfeld, 2008, p. 124), instead of on the perception of it.

The industrial ecologist Ehrenfeld (ibid.) suggests a viewpoint on sustainability by explaining the definition as follows: "Sustainability is the possibility that humans and other life will flourish on Earth forever", and Ehrenfeld proposes this possibility is within reach by means of behavioural change, on an individual as well as a social level.

The latter definition also highlights the knowledge field of socio-cultural innovation, as advocated by, for example, Manzini, who places designers in the role of social actors and refers to them as the most important players able to influence daily life experience (Mestre, 2014, p.28). Manzini (2009) describes design for sustainability as following: "everything design can do to facilitate the social learning process towards a sustainable society. That is, to sustain promising social and technological innovations and to

re-orient existing drivers of change towards sustainability.” Manzini (ibid.) describes sustainable solutions as “product and service systems that propose different ways of being and doing from those currently dominant, lighter in environmental terms and more favorable towards new forms of socialisation.”

The question which arises from the previous paragraphs is whether these definitions are helpful to enable designers to create sustainable products that function within the complexity of the product system. Several models (e.g. the model of the engineering product design process by Cross and Roozenburg, 1992), visions (e.g. the vision in product design model of Hekkert et al. 2003) and frameworks (e.g. the conceptual framework of product service systems (PSS) of Rivas-Hermann et al. 2015) have been developed to structure the relationship between product development and the socio-technical or societal environment in which these products function. To position the aforementioned definitions of sustainability in the context of this thesis, they are reviewed against the multilevel design model (MDM) as described by Joore and Brezet (2013, see Figure 7). This model has been developed with the specific aim to structure the complex system in which designers function and therefore is considered beneficial to the conceptualisation of a definition of sustainability within the context of this research.

It is argued that the definitions of sustainability as described on the previous page work well for stakeholders who operate and exert influence at the (top) Societal System level (S) – where communication by diplomacy is more commonly applied (and possibly required as well); but that designers, operating at the Product Service System (Q) and the Product Technology System (P) are in need of more practical and better specified definitions.

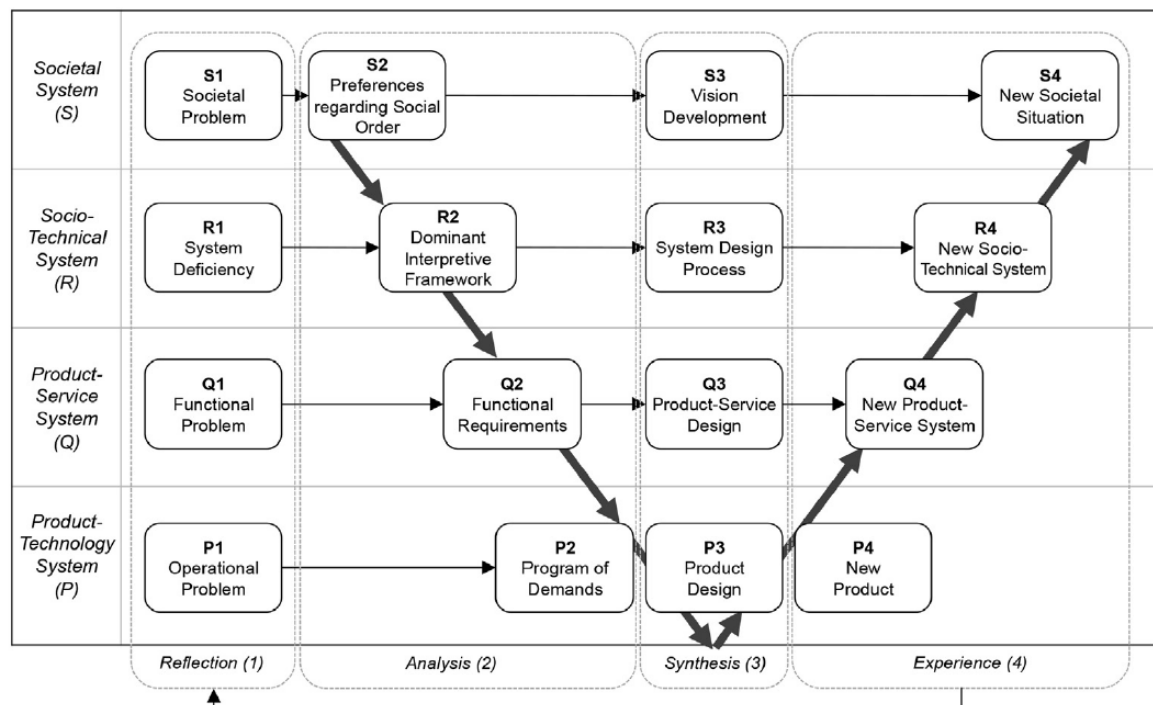


Fig. 7 The multilevel design model (linear presentation; Joore and Brezet, 2013)

The problem with the ‘(S)-level’ definitions in (design) practice might be that they are harder to implement at the lower (Q) and (P) levels because they do not include any norms or value judgements.

Therefore, the results from working with these kinds of definitions might be more difficult to measure and less useful for benchmarking and track and trace, since they implicate *qualitative* research. For this thesis, with the *quantitative* LCA methodology and a metrics related research question at its core (see the hypothesis and RQ1 in Section 1.3), it is important to choose a normative definition of sustainability, which could not be found in the literature. Since the CRQ refers to a transformation, the definition for sustainability used for this thesis is formulated as the preferred situation²¹, namely: 'Sustainability is reached when the ecocosts and s-ecocosts of a product, a service or a system are zero'. By this means, and in advance of the explanation of the applied methods in Section 2.3 and specifically in 2.2.4 about life cycle assessment and ecocosts, the reader is already introduced to the quantitative character of this research.

There are many (English) words to describe **clothing**. Also, there is a confusing aspect in the English language, with various terms for clothing products (or garments) and fabrics, which can be and often are named 'textiles'. Throughout this thesis, these terms are used interchangeably but all refer to the clothing we wear on a daily basis. Furthermore, many other words can be used "to describe the cloth that is used to cover and adorn the body". Breuer (2015, p.30) lists a few: "Clothes, apparel, attire, costume, uniform, outfit, garment, ensemble, vestment, dress".

It is important to clarify the exclusion of two important product categories from this thesis, which are often bracketed together with 'textiles', namely footwear and carpeting. Although there certainly is overlap with reference to input (fibre) materials and fashion cycles, functionality and production methods are different and therefore shoes (and hats) and household textiles are excluded from this study.

Without the wording 'adorn' (see the above quote), the definition of clothing would not be very complicated and could be as simple as: 'the cloth that is used to cover the body' (exactly as described in the preceding section). The use of 'adorn' already adds complexity, because through this, other meanings of clothing, beyond their function come into play. Niinimäki (2011, p.38) describes several meanings of clothing, e.g. by citing Woodward (2005) who "argues that clothing unifies roles with regards to identity, sexuality and sociality, and hence clothing choices externalize the inner self in social contexts". Via Kaiser's (1990) claim that: "clothing can be understood by its cultural context" and Entwistle's (2000) definition: "clothing...mean[s] an embodied experience that is socially constituted and situated"; Niinimäki (2011, p.38) refers to Levy-Bruhl (1966), who indicates clothing to be one of the products that "can be defined to be the extenders of identity", and McCracken (1990) who "argues that clothing is an expressive medium and can be understood as a language or at least as a communication medium" (of which marketing seizes this opportunity, see next section). This is the point also where the meaning of fashion is introduced as referring to the ability of a product to "signify the present" (Miller, 1992). Finally, Niinimäki (2011, p.39) returns to Kaiser (1990), who claims that "fashion is a symbolic product, and it differs from clothing", which is "material production that fulfils

²¹ In LCA vocabulary, one could also refer to the no-effect level for toxic emissions (note that most toxic substances have a toxicity threshold), and the performance reference point (PRP; UNEP/SETAC, 2009) where the social issue is supposed to be resolved.

our physical needs for protection and functionality. Fashion, in contrast, is connected to the user's emotional needs (ibid.). Fashion connects consumers' inner individual personality to external symbols: e.g. brands, status, items, uniqueness, appropriateness and beauty."

Next to clothing, not many other products exist that are so closely linked to **fashion**. Jackson and Shaw (2009, Figure 1.1 on p.5) adapt Maslow's hierarchy of needs and state that "fashion clothing is addressing the top three levels of social needs, esteem needs and self-actualisation needs" (of the consumer). Jackson and Shaw also point out that the consumer sometimes neglects the hierarchy (firstly satisfying hunger before worrying about social or esteem needs) and "prioritises spending on fashion clothing over a healthy diet" (ibid.), which once again underlines the importance of fashion and clothing for people (see preface of this thesis). Furthermore, Jackson and Shaw (2009, p.87) argue that the "... fashion product is the most important part of a fashion marketing mix." Jackson and Shaw (2009, p.87) claim that fashion is:

- what consumers buy (and do not if a fashion product is fundamentally wrong);
- the most common way for people to convey how fashionable they are;
- a brand statement of quality;
- the principal output of a fashion design process;
- the focus for the other marketing mix elements;
- the tangible representation of a brand.

From this context, it could be argued that it is *marketing* that turns clothing into fashion products. But, more in-depth research into fashion theory reveals there are numerous other definitions of fashion, which decouple clothing from its (brands') marketing. Moreover, many of these descriptions do not directly relate to clothing and therefore are less practicable to work with for this research. For example, Kuusk (2016, p.18) uses the definition of fashion from Pan et al. (2015), describing fashion as: "the symbolic, aesthetic and cultural meanings that objects carry, especially the ways in which people use objects to express their taste, lifestyle, social status and belonging to a community".

More directly related to clothing, and therefore assumed to be more practical to work with for this product-oriented research, Kuusk (ibid.) refers to Kawamura (2005) who "proposes a distinction between fashion and clothing: Fashion is produced as a belief and an ideology ..." while "... clothing production involves the actual manufacturing of fabrics and shaping it into a garment."

Summarising the above, several researchers with (among others) roots in the domain of product design (e.g. Kuusk, 2016, p.18 and Armstrong et al. 2015, p.31) refer to the description of Kaiser (1990), who states: "Clothing, considered distinct from fashion, is a material product that meets a physical need for protection and function. Fashion connects consumers' personality to external symbols" (Armstrong et al. 2014). In line with this, Kuusk (2016, p.18) recognises that the consumption of clothing is driven by fashion that is part of the contemporary culture.

Alongside these descriptions, in the thesis *Fashion beyond identity*, Breuer (2015)²² explains fashion in many ways – again linking the concept of fashion more directly to identity – citing a fashion historian

²² In the thesis 'Fashion beyond identity', Breuer (2015) offers a philosophical, new impulse to the debate about sustainable fashion, by proposing to unlink fashion from identity.

(Valerie Steele); an anthropologist (Joanne Eicher); the academic Elizabeth Wilson and visual culture activist Malcolm Barnard. Finally, via the philosopher Gilles Lipovetsky and again Barnard, Breuer, comes up with a workable definition of fashion for this thesis, namely: "Fashion is 'what people wear'."

With reference to the explanations above, for this thesis the decision was taken to work with a set of clear and concise definitions for sustainability, clothing and fashion, namely:

Sustainability is reached when ecocosts²³ and s-ecocosts¹⁷ (of a product, service or system) are zero;

Clothing is "the cloth that is used to cover and adorn the body" (Breuer, 2015, p.30);

Fashion is the clothing that people wear (inspired by Breuer, 2015, p.34).

With regard to the scope and delimitation of this research, the two descriptions: 'innovative' (technologies) and 'promising' (contributions) in the second RQ (see Section 1.3) require extra attention. In this thesis, the widely applicable conception 'innovative' refers to smart textiles and AM (for textiles). These two technologies have been selected out of many options (such as, for example, new developments on bio-based textiles, ultrasonic textile welding or waterless textile dyeing), because (i) these can be referred to as whole garment technologies and (ii) currently these areas receive ample attention from designers as well as consumers and the media (see e.g. for smart textiles, Köhler, 2013, and for AM, Gausemeier, (2011)). From the viewpoint of this thesis, a technology can be considered 'promising' as soon as it leads to improvement of the sustainability of the point of departure (i.e. the base case to which the new product or service is being compared). Referring to the definition of sustainability (on the previous page), the ecocosts and s-ecocosts of the 'promising' technology should be lower than those of the technology to which it is being compared (and preferably as close as possible to zero).

As a consequence of the above founded decision to narrow the research, and to concentrate on the three RQs (Section 1.3), three important topics have been omitted from this study:

(i) The first topic in the field of metrics related issues is research on circular textile design (re-use, remanufacturing and recycling). The main reason to omit this topic is that it has been observed that the environmental profiles for other materials, e.g. metals and plastics, are many times better when recycled, instead of virgin. It is expected that in the case of textiles, the situation will be similar, since so much water and chemical use is connected to the cotton fields and the production of fibres (as confirmed in personal communication with prof. A. Remmen of Aalborg University on 13th November 2015, with reference to reports of several student projects about circular textile design). Several companies (e.g. Patagonia and Teijin) and (LCA-) researchers (e.g. Wang, 2006; Hawley, 2006; Muthu, 2012) have already been quite active in this field, also. Finally, the ecocosts methodology (as explained in Section 2.2.4) provides methods for closed and open loop recycling, which are applicable to textiles as well²⁴.

²³ The ecocosts and s-ecocosts are explained in the Methods Chapter 2, Section 2.2.4.

²⁴ Note that this does not imply that it would not be very interesting to develop and calculate circular textile cases (and collect up-to-date LCI data) by means of the ecocosts, or any other, LCA method.

In this context, it is important to refer to the recent discussion about circular design (also often referred to as cradle-to-cradle design) in an article by De Man and Brezet (2016) in which the authors highlight the pitfalls of the wide acceptance of this concept.

(ii) A second issue that is not further explored in this study is any in-depth research on life time extension of clothing (although it is discussed in the Discussion and Conclusions section of P.1, p.353-355 and calculated in the 6th Ecodesign of P.6, p.322). For corporate clothing, it can be argued that this topic is mainly related to resistance to wear and tear. For fashion, however, it relates to the third omitted area of research, below.

(iii) The third area of research purposely omitted from this study is an in-depth investigation of consumer behaviour and design for behavioural change. This study, having the aim to provide designers ways of contributing to a more sustainable fashion system, does not concentrate on the consumption system associated with clothing. The literature (and private communications with the researchers and designers referred to at the end of this section) highlights that research and design interventions are currently being developed and different groups have already been active in these fields for several years. For example, the Design Research group at Aalto University in Helsinki, Finland, where the Fashion/Textile Futures group (Kirsi Niinimäki) specialises in new perspectives on human-centred design research; the National Institute for Consumer Research, Oslo, Norway (Kirsi Laitala) in cooperation with the Norwegian University of Science and Technology (Caspar Boks), where extensive research on consumer behaviour has been executed; and researchers and designers at the Centre for Sustainable Fashion together with London College of Fashion in the United Kingdom (Dilys Williams and Kate Fletcher) who, among other things, work on the integration of Slow Fashion in fashion design practice to spread this concept under consumers.

Finally, it should be addressed that this research does not broadly elaborate on systems thinking and steering theory. The fact that the designer is part of the (fashion) system comes to the fore in several sections of this thesis (and even in the CRQ), but the research in this thesis mainly describes a practice based approach, aimed at designers and design practice. In the context of this research, the term 'guidance' in this thesis (and in the third RQ) mainly refers to education (of designers) and communication (with designers).

1.5 Outline and title of the thesis

This thesis consists of two parts: The Chapeau (Part I, six chapters) and the Publications (Part II, six publications, accomplished through an exhibition in Annex I).

In this first chapter of the Chapeau (C.1), an introduction to the topic was provided, and the context, the problem definition and the RQs were described. The next chapter of the Chapeau (C.2) explains the purpose of this research, the research approach and the applied methods. Chapter C.3 presents a synopsis of the research results derived from the six papers P.1 to P.6 (see Part II) and the exhibition (see Annex I).

Chapter C.4 includes a discussion on several issues and, finally, the fifth chapter (C.5) presents the overall conclusions of the research. In Chapter C.6, recommendations for actors other than designers are given, followed by advice for further research.

Although extensive and systematic empirical research on the 'role of the designer' is not the focus of this research, this dissertation comprehensively elaborates on this phenomenon, based on the literature and research of many others²⁵ who have been studying this issue. As described in Section 1.1.3., fashion designers have not been very active or well-known as *sustainable* designers as yet. Therefore, it is expected that it would prove helpful to the transformation towards a more sustainable fashion system if designers make better choices for materials, processes and supply chains, from a sustainable perspective. In other words, it would be beneficial to the transformation if designers take up this extra role (and become sustainable designers) by means of including these tasks in their 'portfolio of skills'. The title of this thesis, 'Making Fashion Sustainable', with subtitle 'The Role of Designers', was deliberately chosen to place emphasis on the necessary transition towards a more sustainable fashion production system, which can be accelerated by designers who adopt their responsibility and take up a different role than before, i.e. become a frontrunner of sustainable fashion.

²⁵ For example, the research of: (i) Luttrop and Lagerstedt, 2006; Vuletitch, 2010 and Atkinson, 2011 in section 1.1.3; (ii) Joore and Brezet (2013) in section 1.4); (iii) Mawle et al. (2010) and Lofthouse (2001; 2006) in section 4.1.2 and (iv) Gwilt and Rissanen (2013) in section 4.1.4.

C.2 Purpose, research sequence and methods

2.1 Purpose

From the previous sections, it has become clear that designers (and other stakeholders in the fashion industry) are in need of information about sustainable textile design from a life cycle perspective. Furthermore, it can be concluded that the implementation of scientific LCA research in design practice (including in broader strategic decisions, for example, on a business or governmental level) could be beneficial for the transformation of the fashion industry into a sustainable industry. This leads to the following formulation to describe the goal of this research: The purpose of this research is to inform fashion designers (and other stakeholders in the fashion industry) about what they can do and what they must undertake in order to integrate sustainability into their designs by taking into account LCA results.

2.2 Research sequence

Literature research, executed within the framework of two external assignments for LCAs of textiles (for DuPont USA (2012) and Lantor (2013) in the Netherlands, confidential reports), confirms the finding that LCAs of textile products are still under development, mainly due to the lack of (publicly available and) up-to-date life cycle inventory data and methodological issues that need to first be solved. The first logical step for this research was an LCA benchmarking study of textile products, which could serve as a reference for further elaboration. The results of this first step are documented in the *LCA benchmarking study on textiles* article in the International Journal of Life Cycle Assessment, named P.1 in the Publications Part II of this thesis.

During the research for the benchmarking²⁶, it became clear that the subject of carbon sequestration in bio-based materials has been a subject of debate for years. There is no consensus about how to deal with carbon storage in LCA of textiles such as cotton, but also viscose made from wood pulp or bamboo. This formed the impulse to commence an investigation around this issue, which led to the *Carbon sequestration in LCA* article, again for the International Journal of LCA (see P.2 in Part II).

Contemporary LCSA (UNEP, 2011) not only concentrates on environmental aspects but is associated with social LCA (S-LCA) as well, which, according to Arvidsson et al. (2015), is "a relatively new research field". Whereas, environmental LCA leads to insights based on (quantitative) calculations, S-LCA has not been developed thus far and assessments remain on a qualitative level. As described in the

²⁶... and from discussions between the co-workers in this project, including other researchers (for example Dr. Pablo van der Lugt) working on LCAs of wood based products.

introduction, the current fashion system is associated with several social issues and cannot be ignored. It was decided to contribute to the development of S-LCA by means of providing "... S-LCA with quantitative socio-economic indicators that facilitate decision making by allowing benchmarking between different options in production processes and production chains" (quote from the reviewers' comments). The findings about the current of S-LCA, and the socio-economic costs, are presented in P.3 (submitted to the Journal of Cleaner Production); the third LCA-related article.

From the first article (P.1), it became clear that manufacturing methods of textiles and clothing products can make a big difference in terms of environmental burden. This provided the spur to investigate other methods of clothing production, including co-creation, with the intention to meet RQ 2. Together with two MSc graduate students of the Industrial Design Engineering Faculty of Delft University of Technology, the possibilities of 3D-printed clothing and AM methods were explored. This collaboration resulted in P.4 'Designing (with) 3D printed textiles' and P.5 'Digital design and localised manufacturing', presented at the 5th International Conference on Additive Technologies (iCAT). In publication P.5, RQ 3 is also met, since this research explores more direct communication between designer and consumer.

The LCA research conducted for the first article (P.1) was partially completed during the work for the European FP7 project, 'LCAatogo', about smart textiles (LCAatogo²⁷, 2011). The innovative smart textiles industry is a rapidly growing sector in which two (so far separately operating) industries come together, namely those of textiles and electronics. The main LCAatogo issues were: (1) the rapid expansion of the smart textiles sector; (2) the concern about the knowledge gap among designers (and users) about LCA and life cycle design of smart textile products. Together with Eindhoven University of Technology (Kristi Kuusk) and former LCAatogo colleague Andreas Köhler, the results and knowledge derived from previous research were implemented in an in-depth assessment of a specific smart textile product. This research generated specific conclusions with regards to designing wearable electronic textiles (see P.6). The article *LCA and ecodesign of smart textiles* for the Materials & Design Journal combines RQ 1 (the metrics), RQ 2 (the production processes) and RQ 3 (the communication to designers).

Apart from communication issues in publications P.5 and P.6, RQ 3 comes to the fore in relation to the exhibition 'Fair Made Fashion Lab' in The Hague in 2014. This display of the research underlying this thesis was *the* opportunity to contact the broader public to communicate the research results. The exhibition also yielded valuable feedback through visitors of the installation, lectures and workshops and via the media. To continue with this communication, a second exhibition (named: 'Rhapsody of Ideas for Sustainable Fashion') is currently being prepared (June 2016) to take place during and around the defence date of this thesis (to be expected in November 2016).

²⁷ Within the framework of the LCAatogo project, the author of this thesis developed, tested and implemented an LCA-tool for smart textile designers, together with Andreas Köhler and Conny Bakker of TU Delft and other partners from the LCAatogo consortium.

Figure 8 presents the RQs of this thesis and the pertaining publications. The header of the image shows the CRQ in red. The arrangement of the research questions and 'coins' underneath graphically indicates that publications 1 to 3 (P.1; P.2 and P.3) concentrate on the first research question (RQ 1); Publication 4 on RQ 2; Publication 5 and the exhibitions A.1 and A.2 on RQ 3; and the sixth publication P.6 on all three research questions (RQ 1; RQ 2 and RQ 3). Note that Exhibition A.2 is vaguely depicted because this exhibition, named 'Rhapsody of Ideas for Sustainable Fashion', has not yet taken place but is scheduled for December 2016 – January 2017).

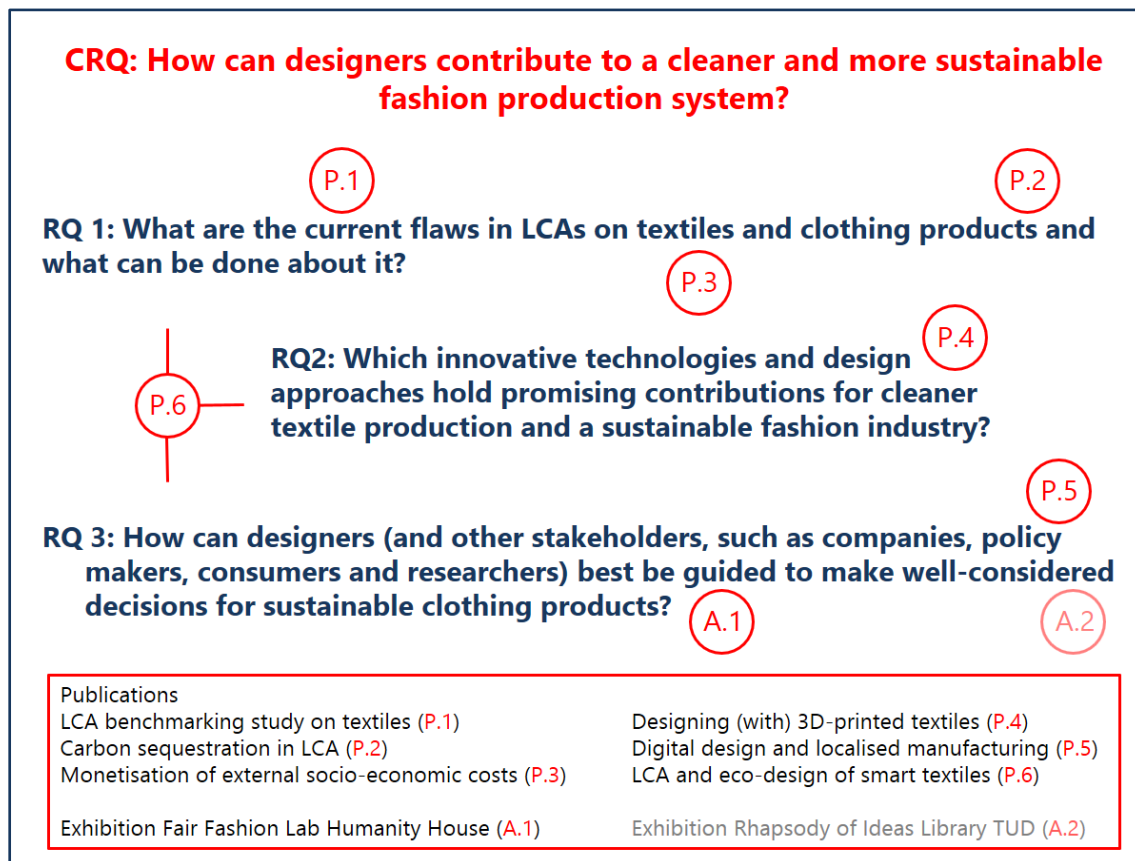


Fig. 8 Research questions and arranged publications

2.3 Methods

2.3.1 Action research and reflective practice

This research project has been designed around two design methods, which allows for interpretation of, and to build on, previous results and conclusions, namely 'action research' and 'reflective practice'.

"Action research is concerned with processes and phenomena that would not have occurred without active intervention from a researcher." (Claesson, 2006, Section 3.1.3) The Action Research approach allows the researcher to respond to findings (e.g. raised questions during the research, results and conclusions) from previous research and formulate new research questions for the next step (publication).

In this project, Action Research as a sub-discipline of design research is not directly related to product design – although all publications are strongly related to clothing products. The progression and results of this particular research project are based upon a form of advanced literary research, rather than on explorative design research based on physical artefacts. Therefore, the term Desktop Action Research is introduced as a name for this type of work and reflects best the working method.

The sequence of the publications, and therefore the passage through the research (as described in Section 2.1), has been guided by Reflective Practice. As Mestre (2014, p.33) describes, citing Schön (1983): "... during reflection in action and reflection on action, ... research problems can be framed, situations can be changed, prioritization made and possibilities offered." This method complements well the Action Research method described above.

2.3.2 Ecodesign and life cycle design strategies wheel

According to the EU (2009) Directive 2009/125/EC "*Ecodesign* means the integration of environmental aspects into product design with the aim of improving the environmental performance of the product throughout its whole life cycle." The UNEP Design for Sustainability (D4S or DfS) report highlights D4S as "... one globally recognised way that companies can improve efficiencies, product quality, and market opportunities while simultaneously improving environmental performance, social impacts, and profit margins" (Crul et al., 2009, p.23). The authors recognise ecodesign as the more limited concept and as part of the broader D4S strategy.

Ecodesign was introduced in the 1990s and since then many scientific concepts, models, methods and ecodesign tools have been developed, of which Sakao (2015), Lindahl and Ekermann (2013, Table 3), Ramani et al. (2010, Fig. 3) and Lofthouse (2006) provide categorisations and pros and cons in the user context.

For this thesis, the choice has been made to work with the ecodesign strategies from the 'life cycle design strategies (LiDS) wheel' (Brezet and Van Hemel, 1995) as an important framework; they are comprehensive, understandable and still recognised as significant design methods (Delft Design Guide, 2015). The eight ecodesign strategies from the LiDS wheel are named in Table 1 in the left column and an example of the LiDS wheel is presented in Figure 9 on page 29.

Table 1²⁸ shows an overview of the ecodesign strategies addressed by the publications in this thesis (see Chapter C.3 for the full titles of the corresponding papers and Part II of this thesis for the complete manuscripts). The first (left) column describes the eight ecodesign strategies of the LiDS Wheel and the plus-signs in the adjacent columns indicate which strategy is dealt with in which publication. For example, in Publication 3 (P.3), the ecodesign strategies 'Choice of materials', 'Production method' and 'Distribution and transport' are represented.

The numbers between brackets below the table refer to the RQs addressed by the specific publications (see also Figure 8 on page 26).

		P.1	P.2	P.3	P.4	P.5	P.6	A.1	
	Name of publication	LCA benchmarking study on textiles	Carbon sequestration in LCA	External socio-economic costs	Designing with 3D-printed textiles	Digital design and localised manufacturing	LCA and ecodesign of smart textiles	Fair Fashion Lab	
	Choice of materials	+	+	+		+	+	+	
	Material reduction				+	+	+	+	
	Production method	+		+	+	+	+	+	
	Distribution and transport	+	+	+	+	+	+	+	
	Impact of use	+	+				+	+	
	Initial lifetime		+				+	+	
	End-of-life	+	+				+	+	
	Alternative function				+	+	+	+	
		(1)	(1)	(1)	(2)	(2)(3)	(1)(2)(3)	(3)	

(1) metrics related (2) production process related (3) communication related

Table 1: Ecodesign strategies addressed by the publications

The hybrid character of the project is highlighted in Figure 9²⁸, where the articles are placed in the context of the LiDS wheel. This image graphically supports the understanding of the accent per publication. In common with Table 1, this graph could help to guide the reader who is only interested in a single specific strategy. For example, Publication P.2 mainly concentrates on the 'Choice of materials' strategy, while in publications P.3 and P.5 the ecodesign strategy 'Production method'

²⁸ These overviews, in Table 1 and Figure 9, are presented to inform the reader about the focus of the papers.

stands out. The position of the 'coin' indicates to what extent the strategy is represented in the publication: the further the 'coin' is placed towards the outside of the circle, the better the strategy is represented in the publication.

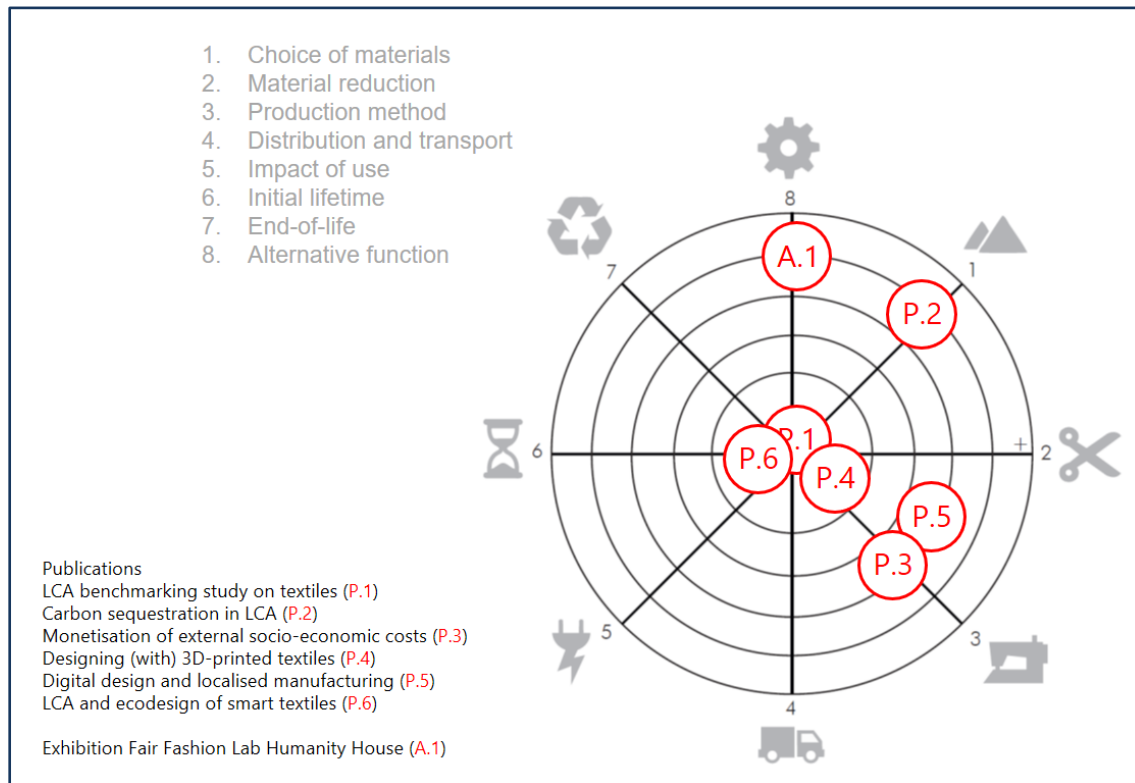


Fig. 9 The positioning of the publications in the LiDS wheel

2.3.3 Life cycle assessment and ecocosts

While the broader concept of ecodesign, ecodesign strategies and the LiDS wheel are qualitative methods, quantitative assessment of environmental impacts (directly related to products, but also to product-systems and processes) can be achieved by means of LCA. LCA is a quantitative method of environmental assessment according to the international standards (ISO 14040 and ISO 14044, 2006): LCA is used to measure²⁹ eco-impact.

²⁹ One could argue that LCA falls under *Metrology*, which is: the science of measurement, embracing both experimental and theoretical determinations at any level of uncertainty in any field of science and technology, (BIPM, 2015), and combines several, perhaps even all, metrology areas.

In Dutch, we have the phrase: 'Meten is weten'. The direct English translation of this phrase is: 'To measure is to know', but could as well be translated as: 'What gets measured, gets done' or 'The numbers tell the tale'. According to Wikipedia, this saying means that by executing quantitative measurements, a clear picture of a certain condition can be achieved.

The method itself, the guidelines and the history of LCA are extensively described publications such as the *Handbook on Life Cycle Assessment* (Guinée, 2002), the *ILCD Handbook* (EU, 2010) and by Guinée et al. (2011).

Environmental LCA (E-LCA) is already a well-established and crystallised method and has, over the past decade, been complemented by social LCA. The Guidelines for Social Life Cycle Assessment (S-LCA) of Products (Benoît, 2010) combine E-LCA and Life Cycle Costing (LCC) and contribute "... to the assessment of goods and services within the context of sustainable development³⁰." (Benoît, 2010, Title)

The UNEP/SETAC Life Cycle Initiative Report *Towards a Life Cycle Sustainability Assessment* (Valdivia et al. 2011) introduces the total concept of Life Cycle Sustainability Assessment (LCSA) and shows how "... the three life cycle techniques ... can be combined as part of an overarching LCSA." (Valdivia et al. 2013, p.1673)

Summarising the above: $LCSA = E-LCA + LCC + S-LCA$ (Schau et al. 2012) and with this equation this summary section about LCA is concluded, in view of readability of this Chapeau. For more information about LCA, and the ecocosts and EVR as briefly introduced below, the reader is referred to the respective references and the publications in Part II.

To date, LCA is the only scientific method to measure the eco-impact, for which a worldwide standard exists (ISO 14040 and ISO 14044, 2006), and with which the scientific community can work and agree upon. So, the decision to work with LCA for this research was obvious.

The *ecocosts* have been developed as part of the model of the ecocosts/value ratio (EVR), to enable LCA calculations (EVR, 2015). In short: The ecocosts represent the amount of money needed for prevention measures, to reduce the damage of eco-burden to zero (the no-effect level).

Recently the ecocosts have been extended with the socio-economic-costs (s-ecocosts), in the first instance for the category of worker only (see further P.3).

The main reasons to choose 'ecocosts' as LCA-metrics for designers are:

- they provide an integrated approach for CO₂ (equivalents³¹), water- and land-use, toxicity and materials depletion, and
- ecocosts, EVR and s-ecocosts include LCA tools, which are relatively easy to understand and communicate, and have specifically been developed for (among others) designers (they provide designers enough information to make LCA calculations and do not trouble them with the detailed background problematic needed to determine the several indicators).

³⁰ The authors emphasize (Benoît, 2010, p.16) that "Sustainability assessment may also require the evaluation of other components that E-LCA, LCC and S-LCA may not be able to include."

³¹ The environmental impact expressed in CO₂ equivalents has a larger scope, because it includes the impact of several greenhouse gasses, compared with the widespread use of 'CO₂ footprint' or 'carbon footprint', which is limited to CO₂ only.

C3. Results

This chapter provides a synopsis of the research results. Each subsection (3.1 to 3.7) describes one publication and begins with the exact reference to the publication in question (see Part II of this thesis for the full versions of the publications). The next explanation summarises the publication by means of a short description of the research in the paper and subsequently presents briefly-worded answers to the underlying RQs³². Each section ends with a paragraph about the contribution of the author of this thesis to the specific publication.

Figure 10 provides an overview of all questions involved and can be considered as an evolved version of the simplified graph in Figure 8 (on page 26). The box at the top presents the CRQ of this thesis and the boxes with the heavy black outlines contain the underlying three research questions (RQ 1 to 3). In the boxes next to the 'coins' P.1 to P.6 and A.1 and A.2., the sub-RQs of the publication are displayed (and usually separate into central and sub as well, see also Footnote 32). The blue arrows indicate the connection between the questions and show which RQ is informed by which publication.

Note that Exhibition A.2 is vaguely depicted because this exhibition, named 'Rhapsody of Ideas for Sustainable Fashion' has not yet taken place but is scheduled for December 2016 – January 2017).

Next to the answers to the questions, each explanation per publication presents relevant extra findings and/or additions that link to the subjects in the discussion Chapter C.4.

The overall analysis of the results leads to the conclusions presented in Chapter C.5.

³² For convenience in reading and understanding, and to avoid the appellations 'sub-' and 'sub-sub', the underlying (central) research questions for each publication are named 'RQ P.1'; 'RQ P.2' etc. The RQs pertaining to the latter are named 'RQ P.1a'; 'RQ P.1b'; 'RQ P.2a' etc. In both, 'P.1' or 'P.2' etc. refers to the publication and 'a'; 'b' etc. refer to the specific RQ (issue) explored within the framework of the particular publication.

CRQ

How can designers contribute to a cleaner and more sustainable fashion production system?

P.1

RQ P.1a Which base textile material for clothing products (cradle-to-gate) has the greatest impact on the environment?

RQ P.1b Which life cycle stage for clothing products per kg textile (cradle-to-grave) has the greatest impact on the environment?

RQ P.1 What is the (cradle-to-gate and cradle-to-grave) environmental impact of textiles and clothing products?

RQ 1 (metrics related)

What are the current flaws in LCAs on textiles and clothing products and what can be done about these?

RQ P.2a How do the recent proposals in LCA to calculate the temporary storage of carbon in bio-based products relate to each other?

RQ P.2b To what extent are they in line with the classical LCA method (as defined in ISO 14044) and the global mass balances as proposed by the IPCC?

RQ P.2c Is there really a need to introduce a discounting system for delayed CO₂ emissions?

RQ P.2 What is the best way to deal with carbon sequestration in LCA (to include in LCAs of bio-based textiles)?

P.2

RQ P.3a Is there a need for accelerated method development for quantitative assessment of social sustainability aspects of clothing products?

RQ P.3b What are the social hotspots (for the category worker) in the textile production chain on the product level?

RQ P.3c How do the s-ecocosts compare with the price of a T-shirt and a pair of jeans?

RQ P.3 Is it possible to measure the (un)social aspects of textile production in Bangladesh via LCA and to inform buyers and consumers in a comprehensible manner?

P.3

P.6

RQ P.6a What are the hotspots over the smart textiles' lifecycle?

RQ P.6b Can ecodesign reduce the environmental impact of smart textiles by 25%?

RQ P.6 Is it possible to improve the environmental profile of smart textiles by means of ecodesign?

RQ 2 (production process related)

Which innovative technologies and design approaches hold promising contributions for cleaner textile production and a sustainable fashion industry?

RQ P.4a Is it possible to design and manufacture clothing products by means of additive manufacturing technologies, such as 3D printing?

RQ P.4b What does the (preliminary) LCA of the 3D-printed clothing product (in this case a corselet) reveal?

RQ P.4 Can 3D-printing become a sustainable alternative for contemporary clothing production in the (near) future?

P.4

P.5

RQ P.5a Is it possible to combine additive manufacturing (AM) and digital design to locally create textile products?

RQ P.5b Is there a market for clothing products designed and produced this way?

RQ P.5c How will digital design and localised manufacturing change the role of the designer?

RQ P.5 Will local, digital garment design be a possible way to ensure the sustainability of (or a part of) the clothing sector?

RQ 3 (communication related):

How can designers (and other stakeholders, such as companies, policy makers, consumers and researchers) best be guided to make well-considered decisions for sustainable clothing products?

RQ P.7 How can sustainable solutions for clothing products best be communicated to a wide audience?

A.1

A.2

Fig. 10 Overview of the research questions

3.1 Publication 1: LCA benchmarking study on textiles P.1

Van der Velden, N. M., Patel, M. K., & Vogtländer, J. G. (2014). LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane. *The International Journal of Life Cycle Assessment*, 19(2), 331-356

This publication describes an improved (up-to-date) insight into the environmental burden of textiles made from the base materials cotton, polyester, nylon, acryl and elastane. The quantitative results were generated by means of LCA and are expressed in ecocosts.

RQ P.1a

Which base textile material for clothing products (cradle-to-gate) has the greatest impact on the environment?

Answer to RQ P.1a

For thin yarns (70-100 dtex³³), woven cotton textile fabric has the greatest impact on the environment, followed by nylon, elastane, polyester and acryl.

For thicker yarns (100-300 dtex), woven nylon textiles have the worst environmental profile, followed by cotton, elastane, polyester and acryl.

Extra findings

In previous and contemporary LCA research on textiles, important technical specifications, e.g. the thickness of the yarn (which has a major impact on processing energy), have not been taken into account. This can be regarded as a major flaw in all LCAs before 2014, because spinning and weaving can be considered hotspots in the production chain.

For spinning, weaving and knitting, the energy consumption per kg yarn is inversely proportional to the yarn size in dtex³⁴. The energy of weaving and knitting is obviously a function of dtex as well, but often not specified in previous studies.

For all fibres, the energy use for the fabric manufacturing process, 'knitting', has a factor 20 times lower than the energy needed for 'weaving'

RQ P.1b

Which life cycle stage for clothing products per kg textile (cradle-to-grave) has the greatest impact on the environment?

Answer to RQ P.1b

In general, and within the scope of this study, the manufacturing stages (weaving, followed by manufacturing of the base material and spinning for cotton) have the greatest environmental impact. This is in contrast with findings in traditional literature about LCA of textiles, in which the use-phase³⁵ is often suggested to be an environmental hotspot over the lifecycle. The reasons for this are: (1) The

³³ 1 decitex = 1 dtex = 0.1 tex = 1 g/10km. The tex is one of several systems to express yarn thickness (yarn count).

³⁴ These findings (for spinning and weaving) were later confirmed by Koning (2013).

³⁵ Zhang et al. (2015) recently reported on the different impact of the laundering behaviour of people in the US in contrast with the situation in China where many people hand-wash with cold water.

energy consumption of household appliances has been reduced in recent years; (2) The introduction of fast fashion has reduced the life span of clothing, resulting in fewer washes per life span.

RQ P.1

What is the (cradle-to-gate and cradle-to-grave) environmental impact of textiles and clothing products?

Answer to RQ P.1

Over the complete lifecycle, and taking into account the goal and scope of the study, clothing of cotton woven fabric of fine yarn (70 dtex) has the highest ecocost, with a value between €5.84 and €6.80 (per kg clothing). This 'worst case scenario' for cotton garments ('bad' material, thin yarn, weaving and despite the credit for end-of-life) is followed by clothing made from nylon, elastane and polyester. The ecocosts of acrylic knitted clothing of coarse yarn (300 dtex) are more than 50% lower, with a value between €2.51 and €3.11 (per kg clothing).

Extra findings

The environmental impact over the life cycle of clothing products can easily be calculated by means of the 'Fast Track' LCA method and the use of open access Idemat Excel files on the internet.

The outcomes of the hotspot analyses remain scenario based (i.e. case dependent), especially for the phases after the fabric manufacturing stage, which are: [E] dyeing of fabric; [F] final finishing including drying; [G] use-phase and [H] end-of-life³⁶.

Additional

Recently, the textile material 'elastane' has received renewed attention (EenVandaag 2016) because former employees of the Lycra³⁷-factory of DuPont in Dordrecht (NL) reported serious health problems, which they connect to the time they worked with this material. One of the claims of the old-employees is that contact with the material caused infertility, due to the toxic characteristics of dimethylacetamide (DMA), which is used as a solvent for elastane fibre production. In 2011, the European Chemicals Agency declared DMA to be a substance of very high concern because of its effect on human reproduction, and proposed the uptake of this compound in the REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) programme (ECHA, 2011). According to prof. J. de Boer (interviewed during the EenVandaag coverage) DMA is released into the air during elastane fibre production and easily penetrates the skin. This means that during the production of elastane special attention must be given to the s-ecocosts of occupational safety and health (OSH; see P.3).

Within this context it should also be noted that for application in textiles and apparel, elastane is normally mixed with other fibre materials in so-called 'fibre blends' (e.g. a basic T-shirt is made out of a blend of 96% cotton and 4% elastane).

³⁶ These phases follow the preceding: [A] fibre production; [B] spinning to yarn; [C] weaving or knitting and [D] pre-treatment.

³⁷ 'Lycra' is the DuPont-tradename for elastane; Bayer used the name 'Dorlastan', and in the U.S. the material is named 'Spandex'.

The text of Publication 1 is largely the work of the first author. The collection of the life cycle inventory data was performed in cooperation with ir. Mylene Geldof, at the time of the project a student at textile engineering school ENSAIT in Lille, France. A large part of this work, including the LCA study and the calculation and interpretation of the results, was done by ir. Natascha van der Velden under the supervision of prof. Martin Patel of Utrecht University. TU Delft prof. (associate) Joost Vogtländer offered valuable insights and comments on the article.

3.2 Publication 2: Carbon sequestration in LCA P.2

Vogtländer, J. G., van der Velden, N. M., & van der Lugt, P. (2014). Carbon sequestration in LCA, a proposal for a new approach based on the global carbon cycle; cases on wood and on bamboo. *The International Journal of Life Cycle Assessment*, 19(1), 13-23

This article describes an LCA-based method of calculating temporary storage of carbon in bio-based products, which can be used for LCA of textiles made from bio-based materials (for example wood or bamboo).

RQ P.2a

How do the recent proposals in LCA to calculate the temporary storage of carbon in bio-based products relate to each other?

Answer to RQ P.2a

Over the past few years – stimulated by the wood industry and in the industry of other bio-based products – the idea arose that a credit (a numerical advantage in terms of environmental impact) should be given to bio-based renewable products, related to the temporary storage of carbon in these products.

RQ P.2b

To what extent are they in line with the classical LCA method (as defined in ISO 14044) and the global mass balances as proposed by the IPCC?

Answer to RQ P.2b

The above idea is not in line with the base-line approach of the ILCD Handbook and PAS 2050:2011. There is, however, also an optional approach via which the credit of delaying emissions is to be applied to bio-based products as well as fossil-based products such as polymers ('the atmosphere does not differentiate between the two types of CO₂').

In this article, a different allocation method is proposed for the way in which the extra global carbon sequestration in forests is taken into account, namely by allocating it to the total global production of wood products. This new approach to allocation is combined with a credit for combustion with heat recovery at the end-of-life. This way of calculating the benefit of carbon sequestration is different from the way the optional calculations are specified in PAS 2050 and the ILCD manual.

RQ P.2c

Is there really a need to introduce a discounting system for delayed CO₂ emissions?

Answer to RQ P.2c

Yes, but not via the classical approach (which is by allocating the extra carbon sequestration in forests to the product), but by using the different allocation method as proposed in this paper (by allocating it to the total global production of wood products), in combination with a credit for combustion with heat recovery at the end-of-life.

RQ P.2

What is the best way to deal with carbon sequestration in LCA (to include in LCAs of bio-based textiles)?

Answer to RQ P.2

In future LCAs, the advantage of wood and wood-based products might better be described in terms of land-use change on a global scale, in combination with the attribution of a credit for heat recovery at the end-of-life (if applicable).³⁸

Additional

For LCAs of textiles made from softwood from the Northern hemisphere (e.g. Europe, North America and Siberia), the credit for carbon sequestration may be estimated at 0.19 kg CO₂ (0.026 euro) per kg dry bio-based textile. The sequestration credit of textile from bamboo is estimated at 0.55 kg CO₂ (0.074 euro) per kg dry textile. Note that these credits are negligible in comparison with other ecocosts for textiles, so this carbon sequestration credit may be ignored.

There is no credit for textile from forest stewardship council (FSC) wood from tropical regions because the system is in balance and, by following Van der Lugt and Vogtländer (2014, p.250), one may argue that there is a debit of about 3.45 kg CO₂, or 0.466 euro, per kg dry textile for unsustainable harvested hardwood, but this type of wood is hardly used in the textile industry.

Next to dr. Pablo van der Lugt, PhD from TU Delft, ir. Natascha van der Velden contributed to the method development as described in this article. Life cycle inventory data collection was mainly done by Van der Lugt and TU Delft prof. (associate) Joost Vogtländer, including the processing and interpretation of the results. The text is largely the work of the first author, while Van der Velden extensively checked the equations, calculations and results and reviewed the paper.

³⁸ In a recent publication, Røyne (2016, p.12) also "... underlines the importance of a consensus process (possibly combined with further method development) for agreeing on the methodology for how to account for carbon dynamics in climate impact assessment in LCAs of forest products." Røyne et al. (2016) propose to include more aspects expected to have a substantial influence, such as climate impact from soil disturbances, indirect land-use change, changes in the albedo and aerosols. They argue that inadequacy might lead to (among others) failure in identifying the preferred product in the decision making process. "Until improved methodology, covering all potentially relevant climate impact aspects, becomes accessible, [they] recommend that LCA practitioners (i) reflect on the decision-making context(s) in which their LCA will and can be used, (ii) consider which climate impact aspects are potentially important for the decision-making context(s), and (iii) calculate or estimate the influence of the aspect(s) quantitatively (e.g. by sensitivity analysis) or, if this is not possible, qualitatively."

3.3 Publication 3: Monetisation of external socio-economic costs P.3

Van der Velden, N.M. & Vogtländer, J. G. (2015). Monetisation of external socio-economic costs of industrial production: A Social-LCA-based case of clothing production. Journal of cleaner production (under review)

This paper presents a benchmark (in ecocosts) of production processes and production chains of clothing products, by means of social life cycle assessment (S-LCA).

RQ P.3a

Is there a need for accelerated method development for quantitative assessment of social sustainability aspects of clothing products?

Answer to RQ P.3a

Yes, because – as the inclusion of environmental LCA (E-LCA) results in the design decision making process shows – well-founded analyses can inform several stakeholder categories to outline the transition towards a more sustainable fashion industry.

RQ P.3b

What are the social hotspots (for the category worker) in the textile production chain on the product level?

Answer to RQ P.3b

For a T-shirt and a pair of jeans, the cradle-to-gate s-ecocosts classify the garment production phase (the sewers on the shop floor) in Bangladesh and Myanmar as a social hotspot over the textile production chain.

RQ P.3c

How do the s-ecocosts compare with the price of a T-shirt and a pair of jeans?

Answer to RQ P.3c

The total s-ecocosts for a T-shirt and a pair of jeans depend on the production chain. Table 2 provides an overview for the cases, as described in the paper.

Indicator	Case 1 (W) T-shirt (€/piece)	Case 2 (A) T-shirt (€/piece)	Case 3 (ABP) T-shirt (€/piece)	Case 1 (W) Jeans (€/piece)	Case 2 (A) Jeans (€/piece)	Case 3 (ABP) Jeans (€/piece)
Fair Wage Deficit	0	0.045	0.241	0	0.135	1.918
Extreme Poverty	0	1.321	0	0	11.668	0
Occ. Safety&Health	0.046	0.095	0.092	0.384	0.759	0.755
S-ecocosts total	0.046	1.461	0.333	0.384	12.561	2.674

W = Western; A=Asian; ABP = Asian Best Practice

Table 2 The s-ecocosts (in €/piece) of a T-shirt and a pair of jeans for different production chains

Extra findings

When the minimum fair wage is paid to all the people in the textile production chain (as specified in this paper), the total extra production costs would be around € 0.43 for a T-shirt and € 3.36 for a pair of jeans (excluding VAT and profit margins).

RQ P.3

Is it possible to measure the (un)social aspects of textile production in Bangladesh via LCA and to inform buyers and consumers in an understandable manner?

Answer to RQ P.3

Yes. The proposed s-ecocosts methodology makes it possible to quantify the following five subcategories for the category 'worker' in terms of s-ecocosts: Fair Wage Deficit, Child Labour, Extreme Poverty, Excessive Working Hours and Occupational Safety and Health.

The quantification of the social aspects in a single monetary indicator allows for easy benchmarking and hotspot analysis.

The text of Publication 3 is largely the work of the first author. Method development, including data collection, calculations and interpretation of the results was done in close cooperation with TU Delft prof. (associate) Joost Vogtländer, who has provided valuable insights and comments on the article.

3.4 Publication 4: Designing (with) 3D-printed textiles

P.4

Lussenburg, K., van der Velden, N. M., Doubrovski, E. L., Geraedts, J. M. P., & Karana, E. (2014, October). Designing with 3D Printed Textiles: A case study of Material Driven Design. In: iCAT 2014: Proceedings of the 5th International Conference on Additive Technologies, Vienna, Austria, 16-17 October 2014. Interesansa-zavod, p. 74-81

This paper describes a design project of a wearable garment by means of 3D print technology, which not only has functional or environmental superiorities but also experiential ones.

RQ P.4a

Is it possible to design and manufacture clothing products by means of additive manufacturing technologies, such as 3D printing?

Answer to RQ P.4a

This publication (which summarises the master's thesis Integrated Product Design (IPD) at the Faculty of Industrial Design Engineering at the Delft University of Technology of Kirsten Lussenburg) describes the design, and prototyping process, of a meaningful garment using 3D-printed textiles. Lussenburg (2015) applied the Material Driven Design (MDD) method of Karana et al. (2015) to create a 3D-printed corselet of polylactic acid (PLA), produced on an Ultimaker 2, via Fused Deposition Modelling (FDM). The project proved it is possible to create a 3D-printed clothing product.

RQ P.4b

What does the (preliminary) LCA of the 3D-printed clothing product (in this case a corselet) reveal?

Answer to RQ P.4b

The final cradle-to-grave LCA of 1 kg of 3D-printed textile (as applied for the corselet under study and for the given scenario) results in total ecocosts of €3.69 per kg, which is comparable to those of woven textiles with a yarn thickness of 300 dtex. The largest part of these costs is determined by the FDM process (51%), followed by the costs of the consumer transport by passenger car (31%).

Extra findings

This paper shows the application of the MDD method to a design process where additive AM is the primary production method for textile manufacturing. The research shows it is necessary to include not only the material, but also the structure and the production process (the so-called 'MSP combination') in the design process. This conclusion led to extrusion experiments with cellulose fibres from paper pulp and an acrylic binder to create a textile-like material.

RQ P.4

Can 3D-printing become a sustainable alternative for contemporary clothing production in the (near) future?

Answer to RQ P.4

The (preliminary) LCA results hold promising results when the environmental impact of 3D-printed clothing is compared with conventional clothing production. But, though the MSP and the product demonstrate the potential for 3D-printed textiles, the research also confirms that the technology is not ready yet to become a serious competitor to contemporary clothing production. Apart from the not yet finalised basic material, the main barriers are: (i) the relative long production time of material extrusion printing, and (ii) the not yet existing envisioned futuristic manufacturing process (from 3D-body scan – via specialised software and machines – to customised garment) in combination with (iii) the implementation of the right business model.

This project, including the writing of this article, was initiated by ir. Natascha van der Velden. The text is largely the contribution of the first author ir. Kirsten Lussenburg, who graduated at TU Delft on the subject under investigation. As a member of the graduate supervision team (consisting of dr. Elvin Karana, prof. Jo Geraedts and ir. Zjenja Doubrovski) Van der Velden offered guidance and feedback throughout the writing process. The article was peer reviewed by a reviewing committee, under the supervision of prof. Igor Drstvenšek, President of the organising committee for iCAT 2014.

3.5 Publication 5: Digital design and localised manufacturing P.5

Stam, C. J., van der Velden, N. M., Rubio, G., & Verlinden, J. C. (2014, October). Redefining the role of designers within an urban community using digital design and localised manufacturing of wearables. In: iCAT 2014: Proceedings of the 5th International Conference on Additive Technologies, Vienna, Austria, 16-17 October 2014, Interesansa-zavod. p. 82-89

This paper describes the research on the application of co-design principles on a local scale by means of exposing the public to a mobile digital knitting machine.

RQ P.5a

Is it possible to combine additive manufacturing (AM) and digital design to locally create textile products?

Answer to RQ P.5a

The 'reflection in action' (Reymen, 2001) research presented in this publication describes the development of a method, that bridges the gap between the 3D print technology and the end-user. During the IPD graduation project, as described in this paper, Cees Jan Stam designed an easy to

reproduce, portable, digital knitting machine that can be used to produce textile products 'on the spot'. The project demonstrates it is possible to locally manufacture a tailor-made 'beanie' (a hat).

RQ P.5b

Is there a market for clothing products designed and produced this way?

Answer to RQ P.5b

The concept of introducing a localised manufacturing tool into an urban community and the direct exposure of the 3D-knitting technology to the customer resulted in a positive response from the general public. By making use of the AIDA (Attention Interest Desire Action) model, Stam (2016) determined that 87% of the test-participants (n=26) would like to use the machine (if technological limitations of the current test-set up and the applied technology are ignored) for small simple garments, and 53% would use it for more complex garments. 64% of the interviewees declared they would definitely use the machine in future. The field-tests with the Wally 120 generated a lot of attention, and the video, 'Print Your Own Beanie' ('Wally 120 Open Knit machine release', in close cooperation with Gerard Rubio), has been viewed over 13,400 times up until now (May 9th 2016).

Extra finding

72% of the respondents claimed the need for better fitting clothes as a reason to start using this type of garment manufacturing, which implies that despite the standardisation of clothing-sizes within the industrial production of textiles, it does not meet the needs of all users.

RQ P.5c

How will digital design and localised manufacturing change the role of the designer?

Answer to RQ P.5c Producing clothing by means of digital AM machines, such as the Wally 120, in a distributed³⁹ production system (Johansson et al. 2005), transforms the role of the designer from creating products that fulfil the needs of the consumer, into designing and defining the tools and design space for the end-user. This way of manufacturing clothing products opens the pathway to a co-creation process via which the users freely design and manufacture their own products (either with, or without, direct contact between designer and consumer).

RQ P.5

Will local, digital garment design be a possible way to ensure the sustainability of (or a part of) the clothing sector?

Answer to RQ P.5

Local knitting is a promising technology for a transition towards a sustainable society, because:

(1) knitting is a technology with low ecocosts, see P.1; (2) local production might be a means to avoid the high s-ecocosts of garment production, see P.3.

³⁹ From Wikipedia (accessed at 07-06-2015): "Distributed economies (DE) is a term that was coined by Allan Johansson et al. in 2005. There is no official definition for DE, but it could be described as regional approach to promote innovation by small and medium-sized enterprises, as well as sustainable development."

Additional

In the evaluation of the graduation report, Stam (2016) confirms that in order for this method of clothing manufacturing to be (more) sustainable (than conventional clothing production), the end-of-life (EOL) of the product should also be taken into account during the design/manufacturing stages. This is because extended life span through product attachment by means of co-creation (Niinimäki and Hassi, 2011, p.1879-1880) is no longer guaranteed as soon as it becomes too easy to replace a product with something new, made by, and just for, you.

This project, including the writing of this article, was initiated by ir. Natascha van der Velden. The text is largely the contribution of the first author ir. Cees Jan Stam, who graduated at TU Delft on the subject under investigation. As a member of the graduate supervision team (with prof. Han Brezet and dr. Jouke Verlinden) Van der Velden provided guidance and feedback throughout the writing process. The article was peer reviewed by a reviewing committee under supervision of prof. Igor Drstvenšek, President of the organising committee for iCAT 2014.

3.6 Publication 6: LCA and ecodesign of smart textiles P.6

Van der Velden, N. M., Kuusk, K., & Köhler, A. R. (2015). Life cycle assessment and ecodesign of smart textiles: The importance of material selection demonstrated through e-textile product redesign. *Materials & Design*, 84, 313-324

This article presents an LCA of a smart textile-based garment and the redesign of the product by means of ecodesign.

RQ P.6a

What are the hotspots over the smart textiles' lifecycle?

Answer to RQ P.6a

The LCA⁴⁰ of the wearable smart textile device for ambulant medical therapy (named 'Vibe-ing') shows that over the lifecycle of Vibe-ing, the production phase (with ecocosts of €33.2) has the greatest environmental impact, followed by the use-phase (€10.6) and the EOL (€1.3).

RQ P.6b

Can ecodesign reduce the environmental impact of smart textiles by 25%?

Answer to RQ P.6b

For the eco-(re)design of Vibe-ing the LCA results are used to inform and guide the ecodesign strategies to be selected. From the LCA interpretation, it is concluded that 'Strategy 1⁴¹ Choice of materials' and 'Strategy 2 Material reduction' are the most promising approaches to reduce the overall environmental impact of Vibe-ing, because the materials (Merino wool and Electrisola yarn)

⁴⁰ The LCA is based on the prospected scenario thought up by the designers of Vibe-ing (and as described in Section 3.3.2 of the article).

⁴¹ The Strategies are derived from the LiDS wheel, as described in Section 2.3.2.

significantly contribute to the environmental impact of Vibe-ing. In addition, 'Strategy 3 Production method' and '6 Initial lifetime' were selected also. Table 3 provides an overview of the ecodesigns, the applied strategies and the respective ecocost savings, and shows for Vibe-ing, three out of six eco-redesign options improve the environmental impact of the smart textile product (expressed in ecocosts) by at least 25%.

	Eco-design strategy	Improvement measure	Eco-costs savings
Eco-design 1a	1 Choice of materials	Replace wool by acryl	Textile body 73%; Vibe-ing redesign 22%
Eco-design 1b	1 Choice of materials	Replace Elektrisola by copper wire	Electr. system 45%; Vibe-ing redesign 33%
Eco-design 2a	2 Material reduction	Minimise usage Elektrisola with 75%	Electr. system 51%; Vibe-ing redesign 36%
Eco-design 2b	2 Material reduction	Omit collar and skirt	Textile body 60%; Vibe-ing redesign 18%
Eco-design 3	3 Production method	Other knitting technique	Textile body 45%; Vibe-ing redesign 14%
Eco-design 6	6 Initial lifetime	Extend lifetime with 50%	Vibe-ing redesign 33%

Electr. = electronic.

Table 3 Overview of the eco-redesign results of Vibe-ing

RQ P.6

Is it possible to improve the environmental profile of smart textiles by means of ecodesign?

Answer to RQ P.6

The research in the publication concentrates on one case study only and from a scientific point of view the results cannot be transferred to smart textile products in general. The results demonstrate that ecodesign significantly reduces the environmental impact of the redesign of Vibe-ing.

Additional

Smart textiles hold high potential to create unique, rich and personalised material experiences, which leads to a rising interest in applications with these materials. When the main purpose of the material in many applications is to evoke such user experiences, it is argued that many required 'smart effects' could be achieved through alternative materials with fewer environmental impacts.

The text of Publication 6, including the conceptualisation of the project, the processing and interpretation of data and results, is largely the work of the first author. Data collection was mainly done by Van der Velden, in cooperation with the co-authors. Dr. Kristi Kuusk, at the time of the writing of the article a doctoral student at Eindhoven University of Technology, provided the information on Vibe-ing. Dr. Andreas Köhler, PhD from TU Delft, contributed to the work by making the LCA base case. During the process, the co-authors provided valuable feedback on the article.

3.7 Contribution 7: Exhibition Fair Fashion Lab Humanity House A.1

Exhibition Fair Made Fashion Lab. Life Cycle Clothing. With IDE MSc graduate Kirsten Lussenburg. <http://www.humanityhouse.org/tentoonstellingen-item/natascha-van-der-velden/>, Humanity House, The Hague, April - December 2014

The exhibition showed how the ecodesign strategy wheel is applied in research into contemporary clothing products and into future concepts for sustainable clothing production.

RQ P.7

How can sustainable solutions for clothing products best be communicated to a wide audience?

Answer to RQ P.7

The exhibition 'Fair Made Fashion Lab' in the Humanity House in The Hague served as a platform to reach a wide audience. The exhibition was visited by more than 8,000 people and received much media attention. The installation entitled, 'Life Cycle Clothing', explored the RQ (in Dutch): 'Hoe meet je de duurzaamheid van kleding' (translation: 'How to measure the environmental impact of clothing products?') and presented the LiDS wheel as a tool to provide insights into the effect of the application of ecodesign. The exhibition appeared to be a powerful tool to reach a wide audience.

Extra finding

The exhibition, as well as the workshops and lectures I gave, were well received and appreciated by the visitors⁴². This is best expressed in an email to me, sent by Jan Piscaer, lector at the Amsterdam Fashion Institute (AMFI), who came to The Hague with the complete educational staff of this institute (translated from the original email in Dutch): "Thank you very much for your presentation. Last Friday was a nice start to our visit to the Humanity House. Your presentation pointed out the importance of environmental analyses of products; a welcome support to our curriculum. Anton Luiken [from textile recycling innovation centre Texperium in Haagsbergen, the NL] also referred to the ecocosts/value ratio of Delft University of Technology yesterday. Nice to notice how things come together now and then."

Additional

It was observed⁴³ that the visitors and workshop attendees understood well the LiDS wheel and the way to work with the ecodesign strategies. This was also the case when they applied the wheel to the qualitative environmental assessment with the aim of implementing the ecodesign strategies in a redesign. A journalist (of the Volkskrant) even asked if there was any intention to develop the LiDS wheel into an 'official' consumer ecolabel. In contrast, it appears that scientists face problems

⁴² The group of visitors was very diverse; ranging from primary and secondary scholars to students from different educational levels, but also needle work hobbyists and employees of NGOs, researchers and artists, etc.

⁴³ The author noticed the same during other workshops apart from the exhibition, for example, during a workshop with fashion students of the Koning Willem I College on 8 April 2016.

understanding the LiDS wheel, which might be caused by the fact that the LiDS wheel is a qualitative tool and does not provides concrete answers with clear numbers.

The Life Cycle Clothing installation at this exhibition was designed by the author of this thesis. Jemma Land and Frederiek Biemans of the Humanity House, curators of the exhibition, provided valuable feedback during the process of conceptualisation. ir. Kirsten Lussenburg, at the time of the project a graduate student at TU Delft, assisted by making the graphical designs.

C.4 Discussion

This chapter includes discussions on several issues that came to the fore during the research, in the papers and from experience with teaching design students and professional designers about sustainable (textile) design. While the discussion sections in the papers (P.1 - P.6) and the sections under the headers 'additional' in Chapter C.3 highlight further deliberations on contrasting findings and possible limitations of the specific studies, this section sheds extra light on a number of discussion items, which so far were not properly addressed in this Chapeau. These explanations have been used to construct and address (parts of the) the conclusions in Chapter C.5 and the recommendations in Chapter C.6.

Discussion items referring to the research results are presented in Section 4.1 and those related to the research process are described in Section 4.2.

4.1 Discussion points in relation to the research results

4.1.1 Final deliberations on research results

The first issue relates to the limitations of quantification and the impossibility to reduce everything to numbers. A reviewer of Publication P.6 highlighted that streamlined LCAs do not exist, since all LCAs require some type of streamlining. For each LCA, decisions must be taken to omit certain data or to replace data with surrogates, because these either could not be found or could not be measured. This remark made the author(s) decide to delete the description 'streamlined' from the final paper and also has implications for the validity of this research, because, in fact, an LCA is based on arbitrary decisions (see Section 4.2.2, where the author reflects on the limitations of the chosen quantitative approach). In the case of research on sustainability, other methods⁴⁴ could yield valuable results, either by themselves or in combination with a quantitative approach. The recommendations in Chapter C.6 present some relevant developments of a more qualitative nature, including, for example, social entrepreneurship (see Chapter C.6).

With social LCA the numerical question is even more obvious. Whereas environmental aspects can be *measured* (to a certain extent, but without doubt better and more reliable every day), many social aspects cannot be calculated. Publication P.3 proposes a method for one stakeholder category (out of 5; UNEP/SETAC, 2009) only, and within this category only five out of eight subcategories could be

⁴⁴ Such as interviews; case studies; interventions and more 'LCA-like' (numerical) techniques, as e.g. material flow analysis (see for example Herva et al., 2012) or input/output analysis (see for example Tsao and Plepys, 2008; and Schömers, 2013).

addressed (for some reviewers of this paper, even the discussion about the latter e.g. concerning child labour, but also the topic of well-being came to the fore, was rather challenging).

Summarising all of the implications for this study could mean that striving for (following the chosen definition of sustainability for this research, see Section 1.4) the ecocosts and the s-ecocosts to be zero might be impossible, because (the perception) of *sustainability* can never completely be reduced to numbers only, nor is it to be expected that widespread consensus on all aspects will ever occur.

After all, there is, however, one thing which is very important to bring to the readers' attention: In research on sustainability, the pitfall lies in intuition; it can be guiding, but must always be validated. In other words: The designer must be aware that 'gut feeling' about sustainability issues does not always lead to ecodesigns; or in line with the quantitative definition of sustainability for this thesis, i.e. to lower ecocosts. Therefore, this thesis appeals to designers to start by systematically calculating the sustainability impacts of the concepts they develop (see the discussion in Section 4.2.2. about validation and generalisation of LCA, in which the impossibility of putting everything into numbers is raised).

4.1.2 Influence of the designer in companies

From the explanation in Section 1.1.3 the following key-actors, which can contribute to a more sustainable fashion industry, were identified: (a) companies; (b) certification bodies; (c) researchers; (d) consumers; (e) policy makers; (f) NGOs (f).

By positioning these stakeholders in a 'stakeholder interest and influence matrix' (see Figure 11), as developed by Ashby et al. (2015), it is possible to reflect on the mutual influence or dependence of the stakeholders (ibid. p.44). To complete the matrix overview, the actors identified in the Swedish study of Roos et al. (2016: consumers, brands, suppliers, sub-suppliers, authorities, investors, media and NGOs) are included in the figure as well. The double arrows show the way the stakeholders interact.

The designer is positioned outside the table, because, in general⁴⁵ and in the current unsustainable situation (see problem definition part 1. in Section 1.2), fashion designers work for companies, which means they can be found in the companies/brands circle. Simultaneously, investors are linked to the same stakeholder circle, exerting influence on the company management.

To further analyse the situation from the perspective of this thesis (i.e. the position of the designer in a *sustainable* fashion industry; the preferred situation), Figure 12 presents the triple bottom line and the ecocosts/value ratio (EVR⁴⁶) methodology, as described in Section 2.2.4.

⁴⁵ Unless they are independent entrepreneurs, but in that situation they work for their own brand/company, which (for this analysis) can be considered as the same situation.

⁴⁶ Apart from the ecocosts and the s-ecocosts, the EVR in particular is not applied in the research presented in this thesis, but many examples can be found in Mestre (2014).

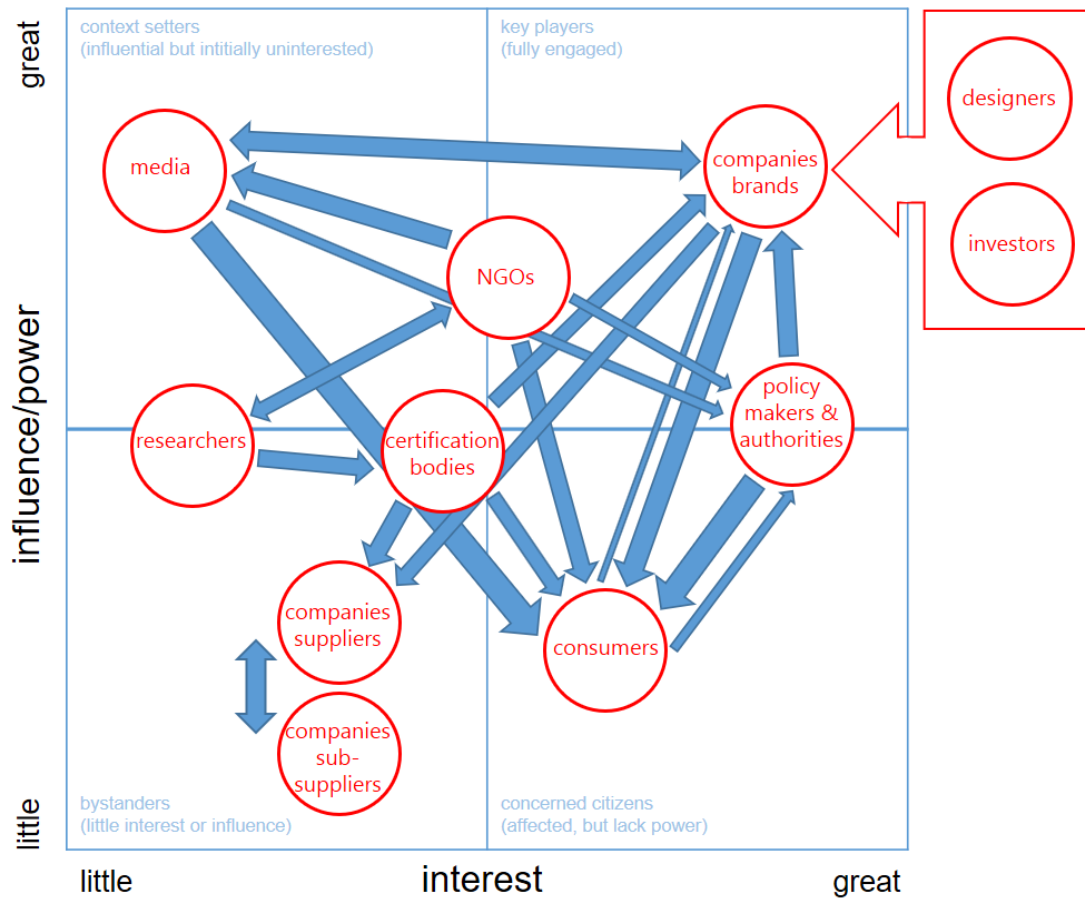


Fig. 11 The stakeholder diagram (adapted from Ashby et al. 2015)

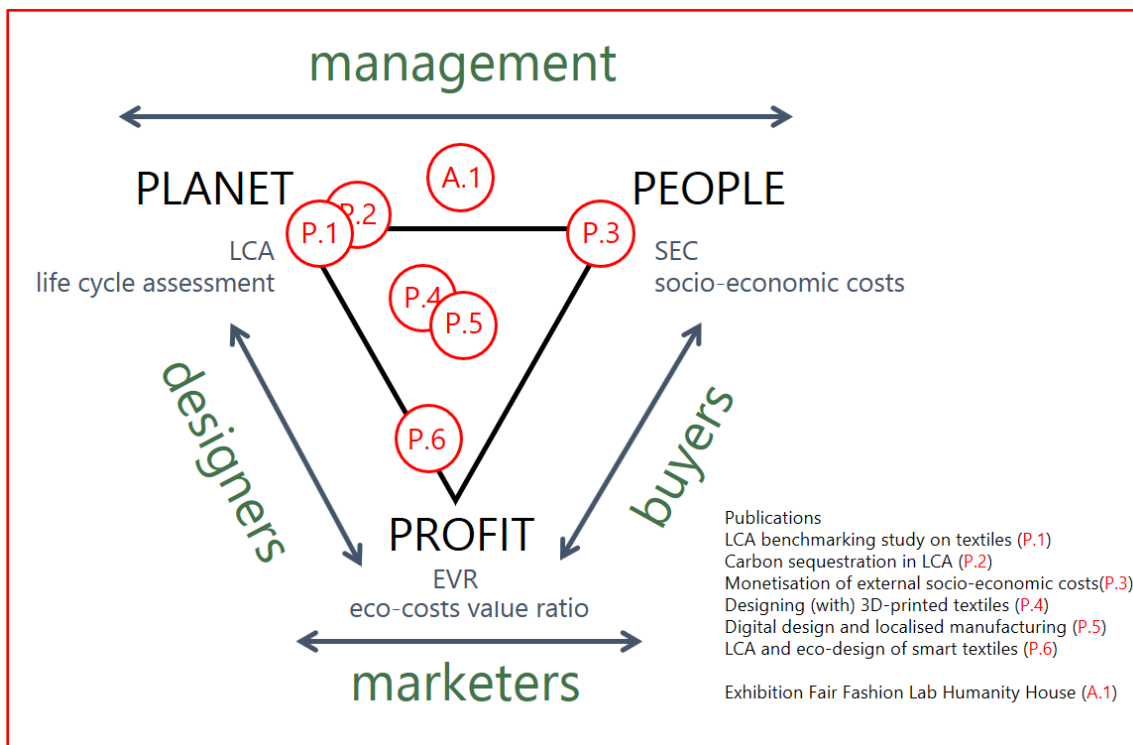


Fig. 12 Influence of actors of fashion companies linked to the triple bottom line

This figure, which can be considered a zoom-in on the companies/brands circle from Figure 11, highlights a number of things:

In the first instance, the management⁴⁷ of the company (steered by the investors outside the company) is responsible for deciding to follow a sustainable pathway by means of adopting the triple bottom line philosophy in all business operations. This first step is considered *the* most important incentive towards a sustainable fashion industry, because this decision is required to enable the underlying company departments⁴⁸ to adopt this perspective (Petala et al. 2010).

Furthermore, the figure makes clear that designers can contribute to two of the three pillars, namely Planet (by taking notice of the theories behind life cycle thinking, ecodesign and LCA and implementing these as much as possible in their way of working) and Profit (by means of creating valuable products). Marketers support Profit by creating value and work together with the designers on eco-efficient value creation. Buyers take notice of the socio-economic costs and use this calculation method to influence their buying behaviour. Through this means there is an equal emphasis on People and company Profit. Although designers (and marketers) do have lesser influence (than buyers) on the People pillar, the socio-economic costs can provide guidance for value creation because, by means of S-LCA (the s-ecocosts), it is relatively easy to calculate the 'true' cost-price of the product.

Figure 12, and the explanations above, indicate that designers⁴⁹ have restricted influence on the implementation of sustainability in companies' strategies (because the management – possibly directed by the investors – determines this) and unbalanced influence on the triple bottom line (not on people aspects, but over Planet and Profit). Although this relative contribution of designers has been subject to constant debate, general consensus applies to the range of thoughts of, for example, Mawle et al. (2010, p.12-13), Lofthouse (2001; 2006) and many others (see Section 1.1.3, but also e.g. Huisman, 2003), to start with sustainable improvement by integrating sustainability as early as possible in the design brief. This is confirmed in the Future Fashion Manifesto (2015), in which it is stated that the design process makes up to 90%⁵⁰ of the decisions that affect the environment.

Linking the above explanation to this research leads to the notion that striving for ecocosts and s-ecocosts to be as close to zero as possible should start as early as possible in the design process.

⁴⁷ Petala et al. (2010, p.182) refer to senior management as 'gatekeepers'.

⁴⁸ Below, these departments are described by their specific role in fashion companies as: designers, marketers and buyers, and indirectly supported by so-called 'facilitating' actors such as administrators and personnel officers.

⁴⁹ Note that the designer referred to in this section is operating at the P- and Q-level of the MDM model (see Section 1.4). There are, however, designers (or entrepreneurs or artists, such as the Dutch Tinkebell) who try to affect the higher S-level, but these can be considered as a minority group. These actors (or activists) might be able to exert more influence on the People pillar, because they fix attention on societal situations.

⁵⁰ In the Future Fashion Manifesto, this percentage is not supported by any reference and is quite high in comparison with contributions referred to by researchers (see Section 1.1.3).

The author again wants to indicate the practice based orientation of the part of the research concerning 'guidance' and 'influence'. Due to time constraints, it was not possible to build this part of the research on extensive governance or other theories from the social and political sciences fields.

4.1.3 Educational level of the designer

The issue raised in the introduction about the educational level of the designer, might need some extra nuance to frame the subject in the right context and to look at it from a different perspective.

As already highlighted in section 1.1.4 many (fashion) designers have not received any education about sustainability or ecodesign⁵¹. Furthermore, Gwilt and Rissanen (2011, p.13) recognise "... that the field of sustainable fashion can appear complex. Fashion designers and consumers are often confused by the language of sustainability and professional resources sometimes do not make clear how people can connect with methods of best practice, creating barriers for engagement with sustainability." It is unclear to what professional resources Gwilt and Rissanen are referring to, but if, in exactly the same sentence as cited above, the notation 'professional resources' would be replaced by 'scientists', this would shed a completely different light on the issue. By this means Gwilt and Rissanen's statement would read as:

"*Scientists* sometimes do not make clear how people can connect with methods of best practice...", and by converting *this* pronouncement to the subject of this thesis, it could be argued that this sentence, above all, describes precisely *the* obstacle that hinders the integration of sustainability in design education. This elaboration implies that to date, scientists (in this research mainly LCA-experts, but also LCA-researchers) have not been able to translate the LCA methodology and LCA results in order that designers can (or preferably are eager) to work with these.

During sustainability courses with BSc⁵² and MSc⁵³ students, but also during workshops with professional designers and engineers within the LCAtoGo project (LCAtoGo, 2013, p.116-118; LCAtoGo, 2016), it was observed that the (would-be) designers, with some help from the instructors (Andreas Köhler, Joost Buiters, Bas Flipsen, Ingrid de Pauw and the author), were able to apply the 'Fast Track' LCA method⁵⁴ to compare relatively simple design alternatives. These (product) designers, however, received middle and higher education at (technical) high schools or university level and were well trained in analytical methods of searching for information in large databases and in presenting and

⁵¹ And some even specifically ask for it, as highlighted in the documentary *Sustainable Fashion Education: The Student Perspective* made by Cosette Armstrong and Kirsi Niinimäki, which unfortunately was recently blocked in the Netherlands on copyright grounds (of the music).

⁵² BSc course: IO2070-14 Technische productoptimalisatie; 2015-2016, Quarter 3

⁵³ MSc course: ID4175 Advanced Embodiment Design Sustainable Design Engineering; 2015-2016, Quarter 3-4

⁵⁴ Vogtländer (2016) describes two groups of LCA: (1) 'fast track' LCA and (2) 'classical' (or 'full' or 'rigorous') LCA. In the case of fast track LCA, the output of the classical LCA calculations is input for the fast track calculation, and the focus is not at all on the LCI and LCIA (as it is for the classical, formal approach), but on the comparison of design alternatives."

analysing data from Excel worksheets. On the other hand, the instructors (ibid.) noticed many of these designers having difficulties with issues such as defining the scope of the LCA and/or the functional unit and also recognising the materials and processes involved. It is expected (and also observed during workshops with fashion students, for example, at a workshop given by the author to students of the Koning Willem I College on 8th April 2016) that for fashion designers from art academies or other secondary educational institutions, these issues might be too complicated.

To elaborate further on this, it can hardly be expected that designers (i) are able to detect flaws in contemporary LCA research (as is done during this PhD research) nor (ii) that they can substantially contribute to the method development of S-LCA. For this, in-depth knowledge of LCA methodology⁵⁵ is required and it is argued (and from the personal experience of the author) that it takes several years to obtain this kind of knowledge. The same reasoning applies for conducting rigorous LCAs on more complex problems, such as the recent publication *An LCA-based approach to guiding an industry sector towards sustainability; the case of the Swedish apparel sector* (Roos et al. 2016); the *Prospective life cycle assessment of an antibacterial T-shirt and supporting business decisions to create value study* of Manda et al. (2015) or the *Cradle-to-gate environmental impact assessment of acrylic fibre manufacturing* of Yacout et al. (2016) and many other LCAs of textiles in (among others) the International Journal of Life Cycle Assessment.

This research proposes LCSA (UNEP/SETAC, 2011) as a method for designers to gain insights into sustainability aspects over a garment's lifecycle and to further act from conclusions derived from this. With the issues raised in this section in mind, two important questions arise:

- (1) Are designers skilled enough to understand and use the S-LCA method? *and/or*
- (2) Did the developers of the S-LCA method make enough effort to translate the method so designers can and will work with it?

Moreover, Gwilt and Rissanen (2011, p.64) raise the question, framing it under the header, 'resistance or inexperience', and looking at it from a slightly different perspective (not specifically referring to LCSA): "Can we attribute this lack of inclusion [of sustainable strategies] to an archaic fashion design process or to the failings of the people working within this system?"

Since the search for the answer to these two questions is beyond the scope of this research, this issue is left open for further debate, but certainly informs the final conclusions in Chapter C.5 and the recommendations in Chapter C.6.

The latter question, (2), and in particular, the words 'can' and 'will', bring to the fore two further issues: (i) The first is that the usefulness of any method (in this context and research (quantitative) LCSA) is dependent on the availability of reliable data, which is an overarching problem raised in the metrics related publications in this thesis (P.1, P.3 and also P.6) and by many other researchers (e.g. Dahlhoff, 2004; Shen, 2011 and Terinte et al. 2014). There is no purpose in a useful and appealing tool with poor background data.

⁵⁵ the development of LCA-methodology (Guinée, 2002; Guinée et al., 2011); the guidelines (ILCD handbook; EU, 2010); the ISO-norms (ISO 14040 and ISO 14044, 2006) and the guidelines on S-LCA of UNEP (UNEP/SETAC, 2009)

(ii) The second point brings the research domain of Lofthouse (2001; 2006) under attention; which is about "... the types of problems faced by designers involved in ecodesign and the type of support they need to make the process of integrating ecodesign easier." Lofthouse (2006) states that "... ecodesign literature shows that many existing tools fail because they do not focus on design ..." and advocates these tools should include a "... combined service of (simple and focused) guidance, ecodesign education and design focused information ...", but also must be "visual" and "inspiring". The work of Lofthouse includes important information for LCSA method developers who want to support the uptake of their domain by designers.

4.1.4 Responsibility of the designer vs responsibility of the company

With regards to CSR⁵⁶, Kogg (2009, p.1) notes that "... attention to corporate social responsibility is necessary to maintain a company's commercial viability and (at least in the long run) corporate profitability." Larsson et al. (2013, p.273) argue that "... external pressures⁵⁷ provide a rationale for corporations to invest in an extended responsibility in the global garment supply chain."

In line with the definition for sustainability pertaining this thesis (see Section 1.4) and the triple bottom line concept underneath, CSR also entails the equal attention (of the company) to all three pillars of the triangle (People, Planet, Profit). Linking this to the discussion in Section 4.1.2, leads to the idea that designers, in their 'centralized role', as Gwilt and Rissanen (2013, p.67) describe the position of the designer in the complex relational system⁵⁸, could support the companies CSR strategy by means of conducting LCA and eco-efficient value creation and simultaneously inform management about this. The above arguments provide the background for a discussion about the responsibility of the company and the (extended) tasks of the designer when the integration of sustainability and CSR in the company's strategy come into play. It is argued that, whereas the company bears responsibility for conducting upstream CSR (by including this in the business strategy), the designer is responsible for transferring present (S)LCA knowledge to the company management. Exactly as designers are used to inform their supervisors about envisioned silhouettes and target groups, material choices, design implications (etc.) and finally cost considerations, they should also inform management about the sustainability consequences their designs entail; even though this information might not reach further than their knowledge allows (see the Section 4.1.3).

⁵⁶ CSR is defined by Kogg (2008, p.61) as "the management of environmental and social aspects that are determined, or occur, upstream within the supply chain beyond the focal company's span of direct hierarchical control."

⁵⁷ i.e. both international and national factors, such as: international labour agreements, local institutional systems, consumer responses to labelling, media's portrayal of the garment industry, increased demand for external reporting by NGOs and the influence of competitors (Larsson et al., 2013)

⁵⁸ Gwilt and Rissanen (2013, 67) specifically refer to micro or small businesses. According to the European Commission (EC, 2013), the textile and clothing sector in the EU is based around small businesses. The EC determined that companies with less than "... 50 employees account for more than 90% of the workforce and produce almost 60% of the value added".

In line with the research on s-ecocosts (see Publication P.3), CSR includes the insurance that all workers in the supply chain are paid at least the minimum country wage, which might have consequences for the price structure of the garments. As suggested in Section 4.1.2, designers can contribute to (eco-efficient) value creation, but the final price setting (which might include the sales price to the middle man; the whole sale; the retailer and/or the suggested retail price) and the mark-up percentage is determined by company management. An analysis of clothing price structures reveals that many different cost-price constructions are in circulation, depending on the structure of the supply chain, the sales-route and intermediate sales. A general picture for a T-shirt is presented by means of two examples in Figure 13. For a pair of jeans, an overview is given by Agarwal (2010) based on CBI (Ministry of Foreign Affairs) market information for the lower, medium and high segments, pointing at wholesalers' margins of respectively 25, 33 and 50% and retailers' margins of 40, 60 and 75%. Schone Kleren Campagne (SKC, 2016; SKC = CCC = Clean Clothes Campaign) summarises, on the Dutch website, that the total production costs of clothing comprise 2-3% of the total costs of the garment and that 'big' brands spend about 25 times more money on advertising than on wages.

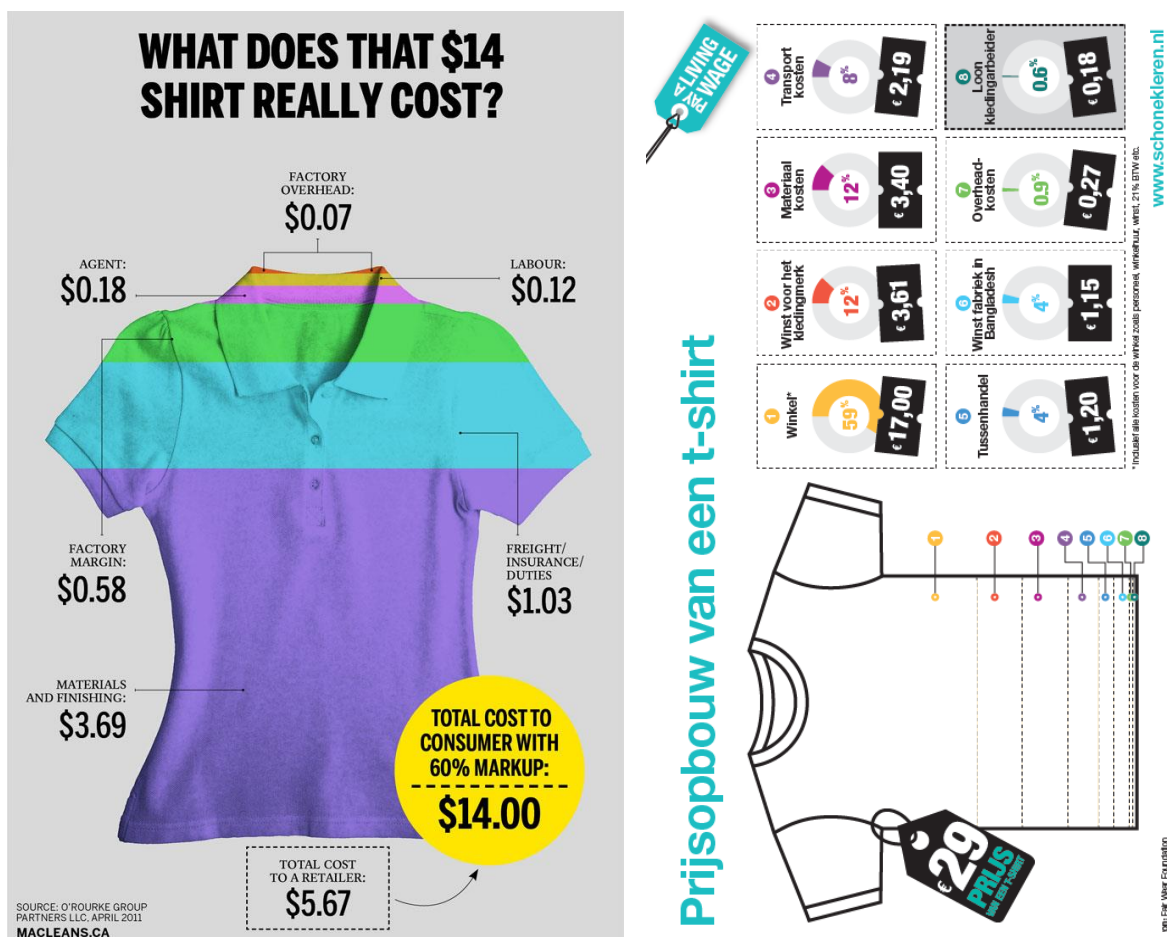


Fig. 13 Price structure of a T-shirt (Macleans, 2013 and SKC, 2014)

The English CCC (2013) website assures that "... total wages are almost never more than 5% of the total retail price ... even for low-price items such as T-shirts offered by budget brands". CCC suggests that "... companies could absorb this negligible increase themselves and the consumer price [c]ould remain the same."

4.2 Discussion points in relation to the research process

4.2.1 The research approach

Near the end of this PhD trajectory, it was concluded that the combination of the early decision to work towards an article-based thesis (and not to choose to finalise this PhD trajectory with a monograph) with the Action Research and Reflective Practice methods worked out in a positive way. Each contributing article could be referred to as a 'mini-thesis'. The selected journals have relatively high impact factors. Hence, each article is associated with a relatively high workload and tough review process. Following publication, there has been time for constructive reflection based on high quality, peer reviewed results, and to consider next steps. It is argued that the methods and this way of working require a highly skilled researcher with vision and a sixth sense, who is capable of managing uncertainties and side-projects at the same time, and is able also to simultaneously communicate at all levels. The author, on occasion, was required to call forth a plethora of skills during a single day, e.g. during the period the Fair Fashion Lab (see Annex I) was built. During this time, to keep all plates spinning, work was required with carpenters and an IDE-student (to build the Life Cycle Clothing installation, see Figure A2), combined with giving an interview with a journalist of the Volkskrant (see Figure A4) and processing a review of the P.6 paper (see Part II: Publications) for the Materials & Design Journal.

Working with students sometimes appeared to be challenging, but the enthusiasm and dedication of those who finished the assignments compensated more than expected for the ones who left the 'battlefield'. It is rather extraordinary that MSc students finish their graduation project with a high grade *and* a conference paper and are asked to contribute to exhibitions and give presentations. The author was happy and proud to mentor two of those extraordinary students (Kirsten Lussenburg and Cees Jan Stam; or actually three, when 'external' student Stephan van Berkel of the Faculty of Architecture of the TU Delft is taken into account as well).

The addition of an external position during a large part of this research (next to a three-year part-time employment for the LCAtogo project) had advantages as well as disadvantages. The positive side was that the combination with the work for my own company allowed for integration of 'external' results into this research (as far as confidentiality allowed). The external periods made it possible to work quietly but, on the other hand, this way of working often required abstention from the valuable coffee-chats and the debates with colleagues.

With 'fashion' and the associated social problems in this sector in mind (see Section 1.1.1 and Figure 5), the idea developed that S-LCA could not be left out from this research; and although at first it was decided to omit the subject (because it appeared to be very broad and not feasible to add to this PhD); it was added to the portfolio soon after the (one year) commemoration of the Rana Plaza (2013) incident. This disaster once more made clear the urgency of the topic and the necessity for method development in this area. With this decision, a complete new (although linked to E-LCA) research field has been tapped, including a new vocabulary, new guidelines, new associated experts and, last but not least, a relatively young, yet unmoulded technique (UNEP/SETAC, 2009). The latter might be one of the reasons that the review process of Paper P.3 has been a challenge so far, although the abstract and the oral presentation of the matter (by the author) were well received during the Global Cleaner Production Conference early November 2015.

Finally, during the last part of this PhD trajectory (the writing of this thesis), it has felt as if it has all come together, with the writing of the results and conclusions moulded into a concise story. Although (and of course), in all fairness, while experiencing the journey, it sometimes felt as if the work was leading nowhere or could never be completed or certainly not be finished within a reasonable time period. After the formulation of the RQs in Section 1.3, it had already been observed that convergence was needed to restrict the scope of the project. The subjects of industrial ecology (i.e. 'the science of sustainability', Leiden-Erasmus-Delft, 2016) and fashion studies (i.e. 'the study of fashion', Rocamora and Smelik, 2016) both have a wide interdisciplinary character, however, and could as well be considered subjects with high complexity. The set of clear suggestions in Section 5.2, based on complicated scientific research (and deliberately formulated in rather uncomplicated wordings to appeal to designers who are appointed as the main target group for this dissertation), can be regarded as a valuable contribution to the body of knowledge of the domain of *sustainable fashion*.

4.2.2 Validity, reliability and relevance of the research

"Validation of engineering research is anchored in the tradition of the scientific method..." (Pedersen et al. 2000) and according to tradition, it demands a formal, rigorous and quantitative approach (ibid.). The validation of this research deserves extra attention because the quantitative character of the research could lead too easily to a judgement on this aspect.

It is a limited viewpoint to state that the numerical approach to environmental issues assures the validity of the assessments because, in this case, there is a (rather complicated) 'model' (method) behind the calculations. The main method used in this research is E-LCA (UNEP/SETAC, 2011), which has been developed by a group of scientists and, despite the numerical character of the method, cannot be regarded as purely mathematical.

It could be argued that the 'LCA-model' is based on subjective decisions; a statement supported by the fact that some important issues are still under debate⁵⁹ and the determination of certain flaws⁶⁰ in LCA by the authors of the publications (P.1 - P.3) presented in this thesis. The above discussion applies also to S-LCA, although the numerical approach to this domain is not as 'matured' as for E-LCA (UNEP/SETAC, 2009) and the approach of the authors of Publication P.3 detailing the s-ecocosts can be regarded as one of the first attempts in this direction.

In the above context, the reviewers' remarks (on the usage of the typification 'streamlined' in connection with LCA) go to the core of the validation of LCA and underline the idea that a full (formal), rigorous LCA does not exist.

Alternatively, after more than 20 years of development, it can be concluded that the LCA method is still consolidating, "... in acknowledging that the current debate is 'about good practice in LCA use and interpretation', rather than about the LCA method itself." (Meursing, 2015b)

⁵⁹ See the discussion points raised in the publications P.1-P.3

⁶⁰ E.g. the omission of yarn count in LCAs of textiles in P.1 and arguably incorrect approach to the carbon sequestration issue in P.2

Since the European Commission (in 2003) declared that “Life cycle Assessments provide the best framework for assessing the potential environmental impacts of products currently available”, both the European Commission and the UNEP/SETAC research group of the United Nations are continuously working on a ‘handbook on best practice’. (ibid.)

With regards to the internal validation of this research and the use of the background data for the LCAs (from for example Ecoinvent, 2010; Ecoinvent, 2014; Idemat, 2012 and Idemat, 2014 for the eco-costs calculations), a similar reasoning applies because these data have been used by a core of LCA-scientists for many years and the references to these databases in scientific publications (among others in the International Journal of Life Cycle Assessment) are numerous. The developers of these widely used databases make much effort to provide as much transparency as possible, this has been continued by the current author(s) to develop data in this research. It has been a basic principle of the author(s) to use data from open-source databases and to clearly present all LCI data (including unavoidable assumptions); bills of materials; analyses and calculations in the publications.

The above discussion on internal and external validation is interwoven with the generalisation of the studies and its results and conclusions. With regards to LCA of textiles in a global supply chain (which is typically the case for textiles, Kogg, 2009, p.9), this aspect is specifically highlighted by, for example, Steinberger et al. (2009), who present a spatially explicit LCI of the global textile supply chain. It is argued that LCAs of textiles are overly complex because of the global character of the industry and the many production stages at different locations all over the world (Farrer, 2011, p.25); and that generalisation of LCI data complicates the validation of LCAs. To offer an example: Water use in cotton cultivation is not an issue in areas with heavy rainfall, but it *is* in countries where water is scarce because of aridity and irrigation is required. The same applies, for example, in the use of energy data, because almost every country (but also local productions facilities) makes use of different electricity mixes (including the use of many other energy sources). These two, rather simple, examples demonstrate the complexity of generalisation of conclusions based on LCA, but many more examples exist. To direct this discussion back to the research results of this dissertation, the databases (for example Ecoinvent, 2010; Ecoinvent, 2014; Idemat, 2012 and Idemat, 2014) that were used for the LCAs in this research, have distinct geographical LCI data⁶¹ and these specific data were applied whenever possible. In cases where the analyses required spatial explicit (or not yet available) data, much effort was undertaken to transparently communicate the acquiring process, the background, and the data in the papers and, by this means, take the spatial aspect of LCI data into account as much as possible.

The generalisation of the research results and conclusions into a broader perspective, e.g. translating these from the case study on Vibe-ing in Publication P.6 to *all* wearable electronics, must be carefully considered. The conclusions in the next chapter, C.5, are valid for the specific case studies in this research and further deliberations are included in this section of Chapter C.4 and in the recommendations in Chapter C.6.

⁶¹ To give an example: Eco-invent provides datasets of cotton from the USA and cotton from China and data for specific country electricity mixes.

This research, and the final conclusions, are based on a sequence of peer-reviewed papers in highly qualified scientific journals. With the above in mind, it can be concluded that this approach underlines the reliability of the study.

The introduction in the first section of this thesis makes clear that it is not solely an observation by the author that the situation with regards to sustainability in the textile sector has become much worse than in 1994 (when the author graduated in the same subject as this thesis, see: Van der Velden, 1994). The many references in Section 1.1.1 indicate the sustainability related problems in the fashion sector are still existent and ongoing, and justify the relevance of this research.

C.5 Conclusions

This chapter provides the answer(s) to the CRQ, 'How can designers contribute to a cleaner and more sustainable fashion production system?', by means of dealing with the three grouped research questions (RQ 1 to RQ 3). In the introduction section, these RQs were formulated as:

RQ 1 (metrics related): What are the current flaws in LCAs on textiles and clothing products and what can be done about these?

RQ 2 (production process related): Which innovative technologies and design approaches hold promising contributions for cleaner textile production and a sustainable fashion industry?

RQ 3 (communication related): How can designers (and other stakeholders, such as companies, policy makers, consumers and researchers) be best guided to make well-considered decisions for sustainable clothing products?

In the next section, 5.1, the answers to these RQs are provided, based upon the research results as described in Chapter C.3 and the discussion points in Chapter C.4.

The conclusions, with regards to the research questions, are presented in sections 5.1.1 to 5.1.3 and categorised under the same headers as the RQs themselves: (1) metrics related, (2) production process related and (3) communication related.

Section 5.2 highlights the conclusions from the viewpoint of the CRQ.

To avoid too much repetition, the answers to the research questions (RQ 1 to RQ 3 in Section 5.1) are not presented straightforwardly but include textual conclusions that construct the final propositions of this research. The conclusions to the CRQ in Section 5.2 are deliberately presented in bullet-points to appeal to the main target group of this research: the practice oriented designer (and again to avoid too much repetition of the same message).

5.1 Conclusions with regards to the research questions (RQ 1 - RQ 3)

5.1.1 Metrics related conclusions

The first research question (RQ 1) – 'What are the current flaws in LCAs on textiles and clothing products and what can be done about these?' – concentrates on the broad domain of life cycle sustainability assessment (LCSA) of textiles. Literature research on LCSA (of textiles) revealed that explorations and calculations in this area (until 2012) did not reflect present-day practices (e.g. an up-to-date LCA benchmark of textile products did not exist). The literature also indicated that certain aspects are not being dealt with in the correct way (e.g. carbon sequestration in LCA of bio-based materials). Other aspects were in need of further development (e.g. the energy dependence of yarn thickness for spinning and weaving and social LCA).

The research, as described in Publications P.1, P.2 and P.3 contributed to the development of LCSA of textiles by:

- (i) presenting an up-to-date LCA benchmark on textile products made from cotton, polyester, nylon, acryl, or elastane;
- (ii) proposing a solution for the carbon sequestration issue in LCA of bio-based materials;
- (iii) developing a method for the quantification of the social impact (for the category worker) of textile products.

From the results and conclusions of these explorations it is possible to consult the designer with clear suggestions for sustainable textile design. The practice oriented conclusions, explaining what designers can do to make the fashion system more sustainable, are presented in Section 5.2.

Based upon this research (P.1 – P.3, including the research in P.6) the following generalised⁶² metrics related conclusions can be formulated:

- LCA research on textiles can only be accurate when yarn thickness is taken into account;
- over the lifecycle of clothing the environmental hotspot is the material manufacturing phase;
- it is not necessary to include a credit for CO₂ in LCA calculations of bio-based textiles;
- the social hotspot over the textile production chain is the garment production phase.

5.1.2 Production process-related conclusions

The second research question (RQ 2) – ‘Which innovative technologies and design approaches hold promising contributions for cleaner textile production and a sustainable fashion industry?’ – was the impetus to further explore innovative production processes for textiles; those which might be considered as sustainable technologies and/or systems in future. With respect to the scope of the research and the delimitations described in Section 1.4, two much-discussed and much-applied upcoming technological innovations were further explored, namely AM (for textiles) and smart textiles. The research pertaining to Publications P.4, P.5 and P.6 leads to the following production process-related conclusions:

3D-printing of textiles

The research described in P.4 shows that 3D-printing (as a form of AM) of textiles could become a sustainable production system in the future, especially with respect to the social issues in production. It will take time to develop the right MSP combination, however, in order to produce a 3D-printed material for clothing products with similar (or better) characteristics than contemporary textiles.

⁶² It is the deliberate decision of the author to present these covering conclusions (and those in Section 5.2) in terms of bullet-points, (i) to avoid excessive repetition of similar information, and (ii) to underline the numerical character of the research and the ‘harsh’ results, which lead to the possibility to construct clear conclusions. For detailed results, discussions and conclusions the reader is referred to Chapter C.3 and/or the full publications in Part II of this thesis.

Digital and localised manufacturing

The research in P.5 on the combination of the digital AM technology with knitting (see P.1 for the better environmental footprint compared with weaving) in a distributed production system holds promising results for the development of a sustainable production and consumption system for fashion.

For this digital and localised manufacturing system to become a sustainable solution for fashion products, it is important that the end-of-life phase of the manufactured product is also taken into account (in the not yet existent LCA of products made by means of this technology).

The shift from mass-production in large factories towards localised small scale manufacturing might bring positive as well as negative effects. An example of a positive effect is the opportunity for entrepreneurial SMEs to think of new business models that might better serve the customer. Whereas a negative effect could be the shift of production back to highly developed countries, reducing employment opportunities in the developing world.

Smart textiles

The environmental performance of smart textiles (wearable electronics) can substantially be improved by means of ecodesign, but designers who design with smart materials should always consider alternative (better) sustainable solutions, through which they will not compromise the targeted user experiences.

5.1.3 Communication related conclusions

The third research question (RQ 3) – ‘How can designers (and other stakeholders, such as companies, policy makers, consumers and researchers) best be guided to make well-considered decisions for sustainable clothing products?’ – in the context of this research and these conclusions, mainly refers to the communication between LCA-researchers (on textiles) and (fashion) designers. The section below describes the communication related conclusions.

This research positively supports the hypothesis (as formulated in Section 1.3) and concludes that the unsustainable fashion industry can be transformed into a sustainable industry by means of providing fashion designers the correct information in order to promote the implementation of scientific LCA research and results in fashion design practice.

Therefore, designers (and other stakeholders) must be educated in (i) life cycle thinking, (ii) ecodesign and (iii) LCA. A powerful and ‘designerly’ way to demonstrate the first two (i and ii) is by means of an exhibition, such as the Fair Fashion Lab of Contribution A.1 (see Annex A.I).

It was observed that the average visitor to the exhibition understood well the background (referring to i and ii in the section above) and applications of the LiDS wheel and the Life Cycle Clothing demonstrators. In contrast, this research shows that the methodology behind classical LCA (iii) and making ‘rigorous’ LCAs of textiles can be rather complicated (and be better taught in a scholarly way than in the form of an exhibition), but that by means of the ‘Fast Track’ LCA method it is possible and relatively easy for designers to compare design alternatives.

As demonstrated in the case study described in Publication P.6, the ecocosts method (in combination with the LiDS wheel) can be considered a useful metric to support the designer to integrate environmental considerations early in the design process and that 'full' LCA is not required for this. Based upon the information in Section 1.1 (problem background and historical overview of sustainable fashion), however, relatively poor integration of sustainability in fashion design practice means that designers will not readily develop and include results of in-depth LC(S)A-research (as produced by LCA-experts and presented in scientific publications in journals such as e.g. the International Journal of Life Cycle Assessment). Therefore, it is concluded that as long as not all methodological LCSA-issues⁶³ are solved, and LCI-databases and appealing design metrics⁶⁴ are still under development⁶⁵, an intermediary must take over this translation task. This suggests the introduction of a new stakeholder to the matrix: the 'tranS-LCA-tor'. The intermediate takes a position between the LCA-expert and the designer, translating LCA knowledge into workable and practical guidelines for sustainable textile design, e.g. as formulated in Section 5.2 (the answers to the CRQ) and in the recommendations chapter, C.6, Section 6.5.

Publication P.5 showed that the designer is able to arouse the consumer's attention in the fashion creation process by means of direct exposure to an innovative clothing (additive) manufacturing technology; in this case, digital knitting on a portable knitting machine.

By directly involving the consumer in the made-to-measure production process of clothing, the consumer is likely to particularly appreciate the better fit of the product and therefore is more likely to keep the garment for a longer period; which (in the end) could lead to less clothing waste.

The analysis of the position of the designer in the company (see sections 1.1.4 and 4.1.2 and Figure 11) leads to the conclusion that the management of the companies, for whom the designer works, have great influence on the (sustainable) level playing field in which the designer operates. It is the board of the company – steered by the investors – who decides whether or not to follow the sustainable pathway. This makes the influence of the designer on the integration of the triple bottom line unequal with regards to the three pillars: The designer can exert influence on Planet (by means of including LCA research and results early in the design process, subsequently limiting the environmental impact of the design), and Profit (by means of creating products with high value); but has less influence on the People aspect (because after all buyers, and management, discriminate certain supply chains and are in charge of the price settings).

⁶³ See the Recommendations Chapter C.6, section 6.4

⁶⁴ For example the Idematapp based on the eco-costs method, see Recommendations Chapter C.6, section 6.4

⁶⁵ Which is work for LCA-experts and design researchers, see Recommendations Chapter C.6, section 6.4

5.2 Conclusions with regard to the central research question

The conclusions (from the publications P.1 to P.6, including the conclusions in the previous Section 5.1) support the proposition that it proves very helpful to the transformation if designers make better choices for materials, processes and supply chains⁶⁶ from a sustainable perspective. One way to do so has extensively been discussed in this thesis, namely, by means of implementing scientific LCA research and results in fashion design practice (for the hypothesis, see Section 5.1 also).

Based upon the research as presented in the underlying contributions (P.1 - P.6 and A.1) and the issues discussed in this Chapeau, the section below answers the CRQ:

‘How can designers contribute to a cleaner and more sustainable fashion production system?’

It would be helpful for the rise of a sustainable fashion industry, if designers:

- receive education on LCA and ecodesign of textile products;
- initially concentrate on the hotspot: the material manufacturing stage (i.e. fibre and fabric production);
- avoid cotton, in favour of acryl, polyester, elastane and nylon;
- design with fabrics made from yarn of the maximum possible thickness;
- choose knitted fabrics instead of woven fabrics;
- accelerate the sustainable transition by means of designing distributed production systems in combination with (digital) AM technologies;
- carefully consider the inclusion of electronics in textiles;
- inform the company management about the (background of the) environmental and social impacts of clothing in general and of the envisioned designs;
- support marketers with marketing sustainable products;
- work only for companies with a consistent⁶⁷ CSR strategy.

5.2.1 Final deliberations on the discussion and conclusions sections in context

To finalise this section, and to introduce the following recommendations chapter, a desirable future is proposed, in which sustainable fashion designers create ‘Life Cycle Clothing’ (products and product service systems) that enhances self-empowerment; firstly of the designers themselves, secondly of the wearer⁶⁸ and thirdly of the maker (no order of importance). By a continuous process of learning, doing

⁶⁶ Taking into account the limited influence of the designer as discussed in the end of the previous section 5.1

⁶⁷ See discussion on CSR section 6.1 and 6.6

⁶⁸ As discussed in section 1.4 under point (iii) consumer research on textiles is not part of this research but some suggestions in this direction are included in the Recommendations Chapter C.6.

and experiencing, self-empowerment of the main actors involved in the fashion chain is considered an essential element to facilitate sustainable development in the sector.

This self-empowerment concept is proposed by the author as the outcome of the thinking process on how to put the empirical research in the wider context of sustainable fashion. This context was sketched in the introduction chapter, C.1, and accomplished by the issues raised in the discussion chapter, C.4, (which add to the problems described in the introduction and inform the conclusions in this chapter, C.5). With the introduction of the concept of self-empowerment, the author suggests that this might be a potential, powerful common denominator within the context of this research. The argument can be explained as follows:

"Fashion as both material culture and as symbolic system" (Kawamura, 2005: referred to by Rocamora and Smelik, 2016) will not soon disappear. These days, fashion designers cannot ignore the sustainability problems associated with the industry they work in. Contemporary and 'future-proof' fashion designers must somehow include sustainability in their way of working. This thesis argues that designers⁶⁹ could realise this by creating fashion⁷⁰ with low ecocosts and s-ecocosts⁷¹.

It is observed (and widely highlighted throughout this thesis) that a straightforward way to make sustainable fashion is not available, and that the current methods are not easy to implement in fashion design practice. If in the future, however, by means of the help of the tranS-LCA-tor and improvement of tools, the designer would be better equipped to conceptualise sustainable fashion, this would help strengthen the position of the designer in the complicated web of stakeholders; in other words: enlarge the designers' self-empowerment.

The link to self-empowerment of the wearer refers to the social dimension of fashion and the strong connection with identity and appearance. A well-known adage in Dutch is: 'Kleren maken de man' (English translation: 'Clothes make the man', which means that a person with nice clothing makes a good impression) and it can be argued that a person's self-empowerment increases when he or she feels comfortable in his or her (responsible) clothing and with the style the clothing represents.

Finally, the self-empowerment of the makers⁷² of the clothing we wear could be enlarged by paying them a living wage and preventing them being exploited or coming to harm. A person who is satisfied with his or her daily work is healthy and has enough money to make a living is likely to be more self-empowered than someone who is not.

It requires no extra explanation that the above 'wanderings of the mind' suggest that further research on all these aspects is needed to underline the 'empowerment quote' of the author (and already provide enough content to put three PhDs to work). The author hopes that this continuing research and the body of knowledge that stems from this thesis will contribute to the rise of a combined group

⁶⁹ As the ones who design clothing products (see definition in Section 1.1.3)

⁷⁰ I.e. the clothing that we wear (according to the definition in Section 1.3)

⁷¹ Following the definition of sustainability in Section 1.3

⁷² In the context of this research referring to: cotton pickers, factory workers and the seamstress

of transition actors (companies, policy makers, consumers and researchers) for sustainable fashion, preferably led by self-empowered designers. Initially, this 'sustainable fashion empowered transition actors network' could be initiated by the tranS-LCA-tor, who will pass on scientific research results and provide the actors 'made-to-measure' LCA-information.

After all, and in line with the subtitle of this thesis, the author calls upon the designer to start to adopt a different role; to become a trendsetter for sustainable fashion (contrary to what many designers currently are, see Section 1.1.3 for an explanation of this observation and Section 1.5 on the subtitle of this thesis).

C.6 Recommendations

This chapter offers recommendations for stakeholders⁷³ other than designers and simultaneously includes suggestions for further research.

In the sections (6.1 to 6.4), each stakeholder is discussed within the context of this research and in order of significance, and each section provides the initial impetus to the answer to the following RQ (derived from the CRQ): **How can <stakeholder> contribute to a cleaner and more sustainable fashion production system?**

Section 6.5 provides guidance to the 'tranS-LCA-tor' (the newly introduced stakeholder in Section 5.1) and presents examples of advice from this intermediate to designers. Finally, Section 6.6 provides an additional suggestion, again for designers, which, according to the author, might be an important incentive to accelerate the transformation.

6.1 Companies

It is widely accepted that (focal⁷⁴) fashion companies should be recommended to pay more attention to CSR⁷⁵. It is open to discussion how useful such a recommendation is, however, since the majority of pre-conditions are lacking in practice:

- (i) at first, the results of the research conducted by Van Bommel (2016) show "... that [focal] companies will need a certain level of capability to react in a pro-active way" ... "to develop a strategy concerning the improvement of sustainability aspects in their supply network." (ibid., p.VII); and for the companies addressed in this section this level of capability is ill-defined (defining this would be out of the scope of this research);
- (ii) and secondly, Van Bommel (2016) found that no integral CSR policy exists in clothing companies yet: "Companies appear to develop different [CSR] strategies and activities for the different themes addressed in societal debates..." and "...T[t]hese activities differ in priorities and level of ambition." (ibid., p.VI).

In summary, it can be concluded that a generalisation of what CSR comprises and what a company should do to include this is currently not specific enough. Hence, there is no value in such a recommendation. Nevertheless, a practical suggestion of van Bommel should be considered: "...t[T]he

⁷³ These stakeholders are depicted in Figure 11. The stakeholder groups 'suppliers', 'sub-suppliers', 'media', 'NGOs' and 'certification bodies' are omitted from this section because they are not key players (or expected to be key players in future) or because they act relatively autonomously.

⁷⁴ Van Bommel (2016, p.32) defines 'the focal company' as: "... an actor in the supply network with a strong and strategic position in the network, which can influence the processes creating the dynamics."

⁷⁵ Although in Section 4.1.4 it was briefly discussed and argued, this attention may be necessary in order for companies to survive.

organisation should become more open for societal debates, willing to learn and cooperate with stakeholders and supply network partners and [be] transparent concerning their activities.”

The same reasoning applies to the commitment of fashion companies to accreditation, certification and labelling schemes (such as the ISO standards 140001 and 26000, ILO standards, the Accord on Fire and Building Safety in Bangladesh, and so-called ‘eco-labels’, for example, the global organic textile standard - GOTS, 2014; EU Ecolabel, 2016 and OEKO-TEX®, 2016).

Van Bommel (2016, p.47) acknowledges that with regards to “.... competing labels (product-related), guidelines, codes of conduct and certification schemes (organisation related) ... A[a]pproaches differ greatly from cooperation to standardisation and coordination.” This refers to many publications about this issue and simultaneously asks and explores the questions: “Who is taking the lead? How are companies selecting what strategy to follow? Which initiative will companies join? Or will they start their own scheme?” After an extensive discussion on many of these schemes, Van Bommel (2016, p.52) concludes that: “As long as collaboration between initiatives will not lead to more integral⁷⁶ sustainability activities, companies will keep on developing their own “tailor-made” strategy within the wide range of initiatives, in reaction to the external pressure.” It is the observation of the author that these ‘tailor-made’ instruments contribute to the confusion among other stakeholders, including designers. Companies should carefully consider the development of such schemes and transparently communicate, (i) why compliance with existing (often widely used and recognised) activities is not possible, and (ii) how the newly adopted scheme has been developed. Without pointing a finger at specific initiatives, after six years of research on sustainable fashion, it is observed that there are many examples of ‘self-made’ instruments that lack transparency and (scientific and reliable) foundations.

From the viewpoint of this research, companies should (instead) make maximum efforts to support their designers to educate themselves in order to equip them to implement (scientific) LCA research in fashion design practice. This means that designers should be given the opportunity to devote certain time per week to this task. When designers understand the principles behind the EVR, and bring these into practice, they will generate more added value, and hence more profit for the company.

Furthermore, in line with this recommendation and the discussion in Section 4.1.2 (and Figure 12), buyers in companies should likewise have the opportunity to learn about social LCA and the socio-economic costs. Marketers should make familiarise themselves with the EVR and how to make maximal use of this method, in cooperation with the designers. In this context it can be argued that the EVR might be the key (for designers and marketers) to convince the company management to include LCA and eco-efficient value creation in their operations. Further research is recommended to underline this statement.

⁷⁶ Van Bommel (2016, P.51) makes the distinction between multi-stakeholder initiatives (open schemes) that focus exclusively on social aspects, and initiatives concerning the environmental aspects that are predominantly business driven and include certification schemes. According to Van Bommel (2016, p.52), ‘integral’ refers to integrated sustainability initiatives for the implementation of environmental and social aspects in the clothing supply chain network.

Simultaneously, companies are advised to broaden their scope, as well as the above advice, to other designers in addition to those who design the clothing products. There are many product-design-related disciplines involved in the fashion industry, e.g. the architects who design the stores, the offices and the factories. An example of a 'tailor-made' sustainable building for the fashion industry is 'The Happy Factory' of MSc architectural student Stephan van Berkel (see Figure 14). Van Berkel (2016) designed a factory especially for the garment workers in Bangladesh, for the location where once the garment factory 'Rana Plaza' stood before its collapse in April 2013. With regards to the shift of the garment manufacturing stage to less developed areas in the world (i.e. to Africa, see Section 1.1.1), companies are advised to consider active interference with infrastructural developments, to prevent such disasters as seen in Bangladesh (and unfortunately in the Far East and Europe and many other parts of the world).

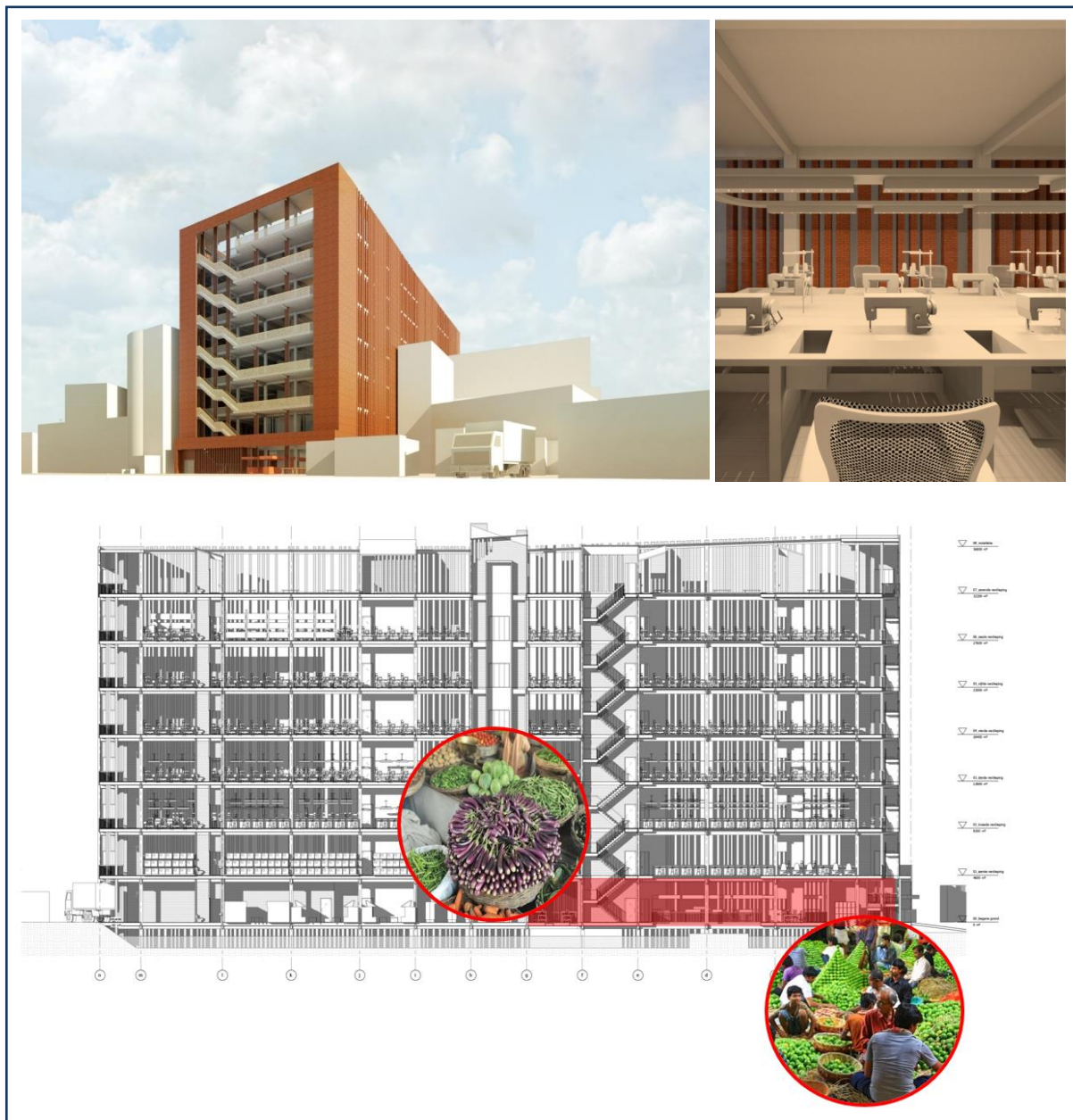


Fig. 14 Impressions of 'the Happy Factory' for garment workers in Bangladesh (Van Berkel, 2016)

Finally, Dutch companies in particular could consider connecting to the recently developed initiative of Dutch Minister Ploumen of Foreign Trade and Development Cooperation, to publish a 'white' list of companies who comply with 'fair trade' (Righton, 2016). This initiative originates from the 'Convenant Duurzaam Kleding en Textiel' (SER, 2016) and, currently, the Dutch government actively approaches companies to sign this agreement. At this moment, the 'white list' includes 60 fashion and clothing companies (with a market share of about 35% of total turn-over) who promise to substantially improve the working conditions in their textile supply chains, including environmental aspects, within three to five years (Righton, 2016).

6.2 Policy makers

The possible execution of the recommendations (to companies) in the previous section is closely linked to the political environment in which the companies (and the designers) operate. It is the institutional landscape, shaped by policy makers, which allows the companies to act.

According to Van Bommel (2016, p.VII) – in favour of the successful implementation process of sustainability in industrial supply networks – policy makers (as one of several stakeholders) "... should stimulate them [companies] to join improvement programmes, and help them become more cooperative and transparent." It goes far beyond the scope of this research to formulate specific recommendations in this respect, but in this context the author would like to refer to the study of Smink (2016), who unravelled the dynamics of institutions and incumbents in the (unsustainable) fossil fuel industry, concluding that "sustainability transitions will evolve along the lines of solutions preferred by incumbents" (ibid. p.163). The results and conclusions of Smink's research cannot directly be transferred to other industrial sectors but it would be interesting to explore whether similar dynamics exist in the fashion industry. A study such as this could support policy makers of all levels to develop an independent vision of the future direction of the fashion industry and to set the rules for the sustainable transformation.

Moving this discussion to a European and Dutch level, it is observed that the (textile) research community and the textile industry is supported by many funding programmes that include sustainable development in general and, more specifically, innovative textile research. Although this observation is encouraging, funding bodies are advised to seriously take the issue raised in the previous section into account and be aware of the mechanisms in place. With this in mind, the author raises concerns about:

- (i) the focus of governments and funding bodies to stimulate cooperation between scientific researchers and industry partners, which could lead to biased and/or undesirable implementation of research results and conclusions in practice;
- (ii) the focus on stimulating research based on 'hypes' (such as 'smart textiles', 'the bio-based economy' and 'bio-based materials' and, for example, 'cradle-to-cradle' a few years ago, which is at the moment replaced by 'circular economy').

It should not be the case that such research (as mentioned under i and ii above) is subsidised at the cost of fundamental textile research and research on the sustainability assessment of textiles, products and product service systems.

Exactly like the 'design decision making process' must be guided by LCSA results (as advocated in this thesis), also governmental institutions should better integrate life cycle thinking and the triple bottom line (see Figure 12) in policy making and likewise in funding programmes.

Political institutions are appointed as important stakeholders to guide the consumer to (and through) the transition process towards a sustainable fashion industry (see Section 6.3). In line with the final recommendation to designers in Section 6.5, governments should stimulate independent social and sustainable entrepreneurship. With reference to this perspective, it is highlighted that this advice does not contradict the recommendation for partial disconnection of business practice (small or large) and scientific research. There are many other ways to bring scientific research knowledge to business communities (e.g. via independent knowledge platforms, educational programmes, exhibitions, symposia, and/or through trans-LCA-tors. See sections 5.1 and 6.5). Policy makers are recommended to establish and maintain the successful existing knowledge transfer mechanisms and to investigate innovative ways for this kind of interaction.

6.3 Consumers

This conclusion is graphically supported by the author of this thesis, as can be derived from Figure 11 and the position of the consumer in the stakeholder diagram. The figure depicts five 'fat' arrows pointing in the direction of the consumer, and only two thin ones in the opposite direction. This indicates that the consumer is intensively influenced by many stakeholders, but that the consumer's influence on the other actors is limited. The confusing situation around eco-labelling for fashion products leads to the recommendation that consumers must be guided to participate in the transition process towards a sustainable fashion industry. It is suggested that designers and policymakers are the two main drivers for this task, and that close cooperation between these could yield beneficial results. A strategy, and topic for further research, might be a combination of, (i) a product designed in a way that encourages sustainable behaviour (see for example Wever et al. 2008 and Daae and Boks 2015) with, (ii) legislation on aspects that cannot properly be met by the design.

There is extensive information for consumers, including consumer guidance, available on the internet. The consistent updating and often transitional nature of such resources makes it unproductive to make a comprehensive search of the currently available information and is considered to be outside of the scope of this research.

From the conclusions of this study, the advice to the consumer could be: Let go of your appreciation of natural materials (e.g. cotton, wool) and consider buying products from bio-based, half-synthetic (viscose and/or viscose-like) or synthetic fibres (acryl) instead. Choose clothing of knitted fabric (of thicker yarns) over clothing of woven fabrics (of thin yarns). Furthermore, the consumer is advised to hang their clothing instead of washing it; and, if the garments are washed (at as low as possible temperature), to not use the dryer, but line-dry the items as much as possible.

Finally, it would be best if consumers use and re-use the clothing as long as possible and, at the end-of-life, hand in all garments for specific waste treatment, e.g. clothing made from bio-based materials for controlled incineration; synthetic fibres for recycling (see Section 6.5); and wearable electronics for specific electronic waste treatment. This regulation of the end-of-life flow might be best executed via collective clothing collection systems, because the consumer may not be able to distinguish the different fibre materials and many fabrics consist of fibre blends.

Furthermore, future LCA research (see Section 6.4) must determine what the optimal end-of-life routes are for the many different fabric materials used for clothing.

6.4 Researchers

For these recommendations, a distinction is made between two groups of researchers: LCA-experts and design researchers. LCA-experts must continue improving the LCA methodology (although the main building blocks are there) and producing up-to-date LCA research and (open) LCI data (of textile products). Remaining LCA-issues, which could be a topic of further research are, for example:

- water use and land-use over the textiles lifecycle;
- prevention costs versus damage costs (see, for a discussion, Vogtländer, 2016, p.91-92);
- toxicity of textile materials (e.g. elastane) and additives over the textiles lifecycle;
- the expansion of the s-ecocosts to other stakeholder categories (for LCSA-experts).

Design researchers and LCA-experts should closely cooperate to accelerate the development of useful LCA-metrics such as the Idematapp (developed by TU Delft IDE MSc student Marinus Meursing, 2015a). Although higher educated designers can work with the ecocosts method and make calculations in Excel, it is expected that a larger group of designers could benefit from appealing and better customisation (Lofthouse, 2006), yet scientifically sound, design tools for integration of LCA in design decisions.

Research on the development of the MSP composition for AM of textile-like products in combination with innovative business models aiming at customisation (and co-creation) must continue. This combination entails a promising direction for sustainable production and consumption systems, although the reunion of digital technology with DIY (do-it-yourself) must be considered carefully due to considerations of increased consumption (Maldini, 2016, p.153), particularly when applied in an unsustainable manner.

Other interesting areas for designers to further explore (preferably in cooperation with LCA-experts) are:

- the optimal mix of yarn count (thickness) and fabric weight for the required function;
- improvement of characteristics of knitted fabrics and knitting technology;
- non-woven materials (in general and made of bio-based polymers or via 3D-printing);
- sustainable circular solutions (including distributed systems) for the fashion industry, e.g. by means of integrating the QWERTY/EE model of Huisman (2003);
- optimal end-of-life route per base material per clothing category;
- the application of the EVR on (product service systems for) clothing products.

Design researchers and industrial design engineers are encouraged to intervene much more with fashion designers and to start ‘thinking through fashion’⁷⁷ (Rocamora and Smelik, 2016). Although design research is a relatively young discipline⁷⁸, fashion research is even younger. To date, eight ‘modedoctoren’ (Dutch for PhDs on fashion) have completed their doctoral thesis (Corstanje, 2013)⁷⁹ in the Netherlands, and three (including the author of this thesis) are about to finish.

“Structured reflection on design processes can help designers to improve their design process, its results, and the designer’s proficiency. Domain-independent design knowledge (as distinguished from domain-specific knowledge) is useful to improve design processes in various design disciplines” (Reymen, 2001, p.3). With this connotation, Reyman (2001) reflects the opinion of the author of this research; that the integration of design research and fashion research (and the stimulation of scientific research on fashion) would help fashion designers to better “...design for inclusion, repair, co-innovation, and involve many more stakeholders as agents and actors”, as suggested by, for example, Von Busch (2010) and Ballie (2012). It is also expected that cooperation could lead to better designed customer oriented clothing products, with reference to design research to encourage consumers to repair clothing instead of discarding it, as well as design to enlarge personal attraction (e.g. as described by Sahni et al. 2015 and Niinimäki and Koskinen, 2011), to prolong the lifespan of garments (see Section 6.3).

Two final suggestions for researchers and designers are related to the restricted influence of the designer in companies (see Section 4.1.2 and the next Section 6.5). (i) It could be interesting for design researchers to analyse how much influence designers have on the Sustainable Development Goals, which were adopted last year (2015) by the United Nations Member States. This could lead to the creation of the *sustainable development (design) method* as described in Annex II. (ii) As a follow-up to these studies’ practice based research on ‘influence’ and ‘governance’, the author recommends further research on the data and findings from a governance theoretical perspective. For example, in relation to the research of Borrás and Edler (2014).

⁷⁷ Three examples: (1) Sullivan (2016, in Rocamora and Smelik, 2016, p. 43) suggests to rethink fashion through Marx to deepen our critical understanding of [fast] fashion as ‘the child of capitalism’. (2) Smelik (2016, in Rocamora and Smelik, 2016, p. 180) proposes the possibility to “... develop an ecological perspective on sustainability through the idea of a ‘becoming-world’ (Deleuze and Guattari, 1994)”. (3) Entwistle (2016, in Rocamora and Smelik, 2016, p. 281) highlights that “Future ANT [actor-network-theory] research in this area can allow us to trace the nature-culture hybrid nature of fashion.” Entwistle (ibid.) names, for example, ‘water’ as an actor within the fashion industry and claims that natural things, such as water, are going to shape the fashion system of the future. Entwistle (ibid.) proposes that it would be interesting, for example, by following Shove et al. (2007), to examine “...‘the stuff’ of fashion in all its fullness within our everyday life”.

⁷⁸ Design research in the Netherlands is about 30 years old. According to an estimate by prof. J.C. Brezet (personal communication d.d. 28-06-2016), in this period, about 200 design research PhDs finished their doctoral thesis (110 IDE TU Delft; 30 TU Eindhoven; 20 TU Twente and 30 Design and Innovation).

⁷⁹ Corstanje (2013) mentions: Daniëlle Bruggeman, Maaikje Feitsma, Anja Köppchen and Constantin von Maltzahn. Via personal communication (at 07-06-2016) with Hanka van der Voet of ArteEZ, Arnhem, the names of Pauline van Dongen and Lianne Toussaint (not finished yet) and Rebecca Breuer were added to this list. Finally, the earlier cited researchers Andreas Köhler, Kristi Kuusk and Harry van Bommel could also be considered as ‘modedoctoren’ from the Netherlands’.

6.5 TranS-LCA-tor

The conclusions in Section 5.1 were slightly unexpected with the introduction of a new stakeholder to the scene: the tranS-LCA-tor.

In general, this tranS-LCA-tor should:

- teach designers about life cycle thinking, ecodesign and LCA and useful LCA-metrics, such as the ecocosts and s-ecocosts;
- work on the development of publicly available LCI- data and design metrics for LCSA.

More specifically, the tranS-LCA-tor could inform designers about the value of life cycle thinking, ecodesign and LCA by means of the following illustrative examples⁸⁰:

(i-a) Manda et al. (2015) describe prospective LCA results of T-shirts made of 50% antibacterial fibres with silver nanoparticles (coated on modal staple fibres via different processes). Through a cradle-to-grave comparison, Manda et al. (2015) demonstrate that the antibacterial T-shirt with the in-situ processed silver, exhibits 20-30% lower environmental impacts than non-antibacterial modal T-shirts (referring to important categories such as climate change, freshwater toxicity and eutrophication). Finally, Manda et al. (2015) conclude that the "... LCA demonstrated value creation opportunities such as lower environmental impacts, lower costs and risks".

De Clercq (2008) designed a (workwear) T-shirt with ventilating armpit areas and lighter fabrics to reduce perspiration prone areas and/or clammy, smelly (polo)shirts.

Based upon this information a sustainable designer, working for the apparel brand or retailer who sells the antibacterial T-shirts, could propose, for example, to apply the silver nanoparticle fabric only in the armpit, and not over the complete T-shirt, as the research of Manda et al. suggests. Design based on the careful application of such technologies could deliver the customer the same experience as the complete silver T-shirt, namely 'no smell', since the armpits are the most sweat prone and least ventilated areas. Because the nanoparticles cannot be detected by the eye, the customer would not even notice the difference (between a complete or partial silver-coated T-shirt) and is expected to be as satisfied with the 'armpit design' as with the complete silver-coated T-shirt. So, it can be argued that the customer would even be prepared to pay the same amount of money for the new (armpit) design as for the old (completely silver coated) T-shirt, with much less (expensive and less sustainable) silver to produce it. To conclude: This new 'armpit' design would lower the production price and the ecocosts while the consumer price could be kept as high as the price for the complete silver T-shirt.

(i-b) Another sustainable concept that elaborates further on this example could be the replacement of the silver-coated part in the armpit with natural wool, which, it can be argued, has the antibacterial property naturally without further treatment.

⁸⁰ In this section, the author provides some examples to demonstrate the way of thinking (of the tranS-LCA-tor), but this overview should be considered as an exemplary, non-extensive list and could be extrapolated much further with many more examples and possible scenarios (in prolongation of the conclusions of this thesis in sections 5.1 and 5.2 and the suggestions for further research in Section 6.4).

(i-c) But also the idea of replacing the modal with a blend of 80% Recycled polyester/20% Organic cotton, as proposed by De Clercq (2008); or replacing the latter in this mix with a viscose could deserve further exploration.

It speaks for itself that the new concepts should be analysed by means of LCA to validate the claims made in this section.

(ii) The integration of solar panels in clothing to generate power for charging mobile phones or other electrical devices is sometimes promoted as a sustainable solution (Van Dongen, 2013).

Ashby (2015, p.9-10) investigated the articulation: "Grid electric power – and, by implication, carbon emissions – can be significantly reduced by charging mobile phones with solar power" with the prime objective "to reduce energy and carbon from non-renewable sources by using solar chargers instead." Applying a relatively simple calculation, Ashby demonstrates that a solar charger (with an internal 800 mAh lithium-ion battery with a life of 2 years) does offer a net reduction in energy consumption, but that the saving is of the order of 0.1% of the annual electricity consumption of the complete British population. Ashby (2015, p.10) concludes finally that: "There are probably simpler ways to save this much energy."

The above example highlights that having a notion of life cycle thinking and being able to make an LCA⁸¹ could withhold a designer from the idea of integrating solar panels in clothing, because this combination might not lead to a sustainability gain (or at least not with this combination of materials and technologies).

(iii) The research of Shen (2011) includes rigorous LCAs of bio-based polymers (to replace the traditional petrochemical polymers) and recycling options for several fibre materials and indicates that man-made cellulose fibres such as viscose and modal⁸² offer potential in terms of reduced environmental impact⁸³. Meanwhile, new research results became available (see for example Future Fashion Manifesto, 2015; and also the research on carbon sequestration in Publication P.2 of this thesis points in this direction) consistent with those of Shen (2011). These findings entail strong indications that the widespread replacement of, for example, cotton fibres (but also PET) by viscose, for clothing, might be a sustainable route for the fashion industry (provided that certified wood or plant material is being used⁸⁴).

Research, such as that above, has led to the idea⁸⁵ that the benefits could also be seen if applied to other plant-based feedstock materials (polysaccharides) such as, for example, grasses like Miscanthus and New Zealand flax, supplying designers with important directions for material choices. Summarising

⁸¹ Ashby et al. (2015) do not apply LCA according to the ISO-standards, so at this place it would be better to name the analysis an 'LCA-like calculation' or an 'Eco-Audit' (Ashby et al., 2015). Conducting a LCA for the wearable solar concept might be more complicated, but nevertheless this discussion could be an indication that the issue is worthwhile to further investigate.

⁸² preferably produced by an integrated process

⁸³ Shen (2011) analysed non-renewable energy use and greenhouse gas emissions at first, and in a second study also cumulative energy demand – CED; water-use; land use and the CML baseline impact categories.

⁸⁴ and the integrated production process is applied, in which the chemicals and water are re-used and recycled

⁸⁵ in the Netherlands at first adopted by DutchSpirit and later taken over by Dutch Awareness

the above: Cellulosic fibre materials for clothing could be a very successful approach for cleaner production of fashion, but each scenario needs to be further elaborated on and analysed from a life cycle perspective in order to prevent undesirable trade-offs⁸⁶.

(iv) It is an observation of the author that designers sometimes mix up manufacturing methods for fibres (and fabrics) and are in favour of natural textile materials. This is important to keep in mind⁸⁷ because the results above cannot be converted to all plant-based fibre materials, since the impact (among other things) depends on the manufacturing method (mechanical, chemical or a combination). Hemp is often considered a sustainable base material for fibres and fabrics but Van Eynde (2015) highlights that the degumming process, which is necessary to produce hemp textile for clothing⁸⁸, causes significant environmental impacts due to the high energy demand of this manufacturing method. This means that for clothing purposes, the environmental impact of hemp (produced in China) might be higher than that of cotton (ibid.), although in the cultivation phase this is the other way around. Therefore, a full LCA is required.

(v) By combining the findings of (iii) and (iv) the designer could consider the processing of hemp via the viscose process, to produce textiles, and consider this a sustainable option. Similar combinations could be made for cradle-to-grave or cradle-to-cradle analysis of life cycle scenarios (including end-of-life) of, for example, incineration versus recycling of bio-based textiles or chemical versus mechanical recycling and/or (in comparison with) recycling or incineration of clothing made of synthetic textiles, etc.

(vi) Bly et al. (2015) explore the intentions of sustainable fashion pioneers who "... actively create and communicate strategies for sustainable fashion behaviour that can overcome the nebulous and somewhat paradoxical reality that sustainable development in the fashion industry presents." One of those strategies is DIY and encompasses sewing or upgrading one's own clothing. The designer who aims at this strategy (by encouraging more consumers to adopt DIY) must take into consideration that (for cotton clothing) this strategy certainly lowers the socio-economic-costs⁸⁹ of garment production (compared with, for example, the Bangladesh situation) but not the (environmental) ecocosts of the cotton and fabric production phase. With regards to the environmental impact, the emphasis over the textiles lifecycle (of cotton products) lies on the manufacturing stages of the fibre, yarn and fabric (see P.1 of this thesis) and the DIY strategy does not change this (unless the fibre, yarn and fabric is made in a 'sustainable' region, but this information is probably unavailable). In the case of DIY, the relative negative environmental effects from the manufacturing stages of the fabric could be traded off by the longer lifespan of the product because

⁸⁶ For example: In case the customer is not willing to buy viscose clothing instead of cotton -, there is no use in producing these.

⁸⁷ and already analysed and discussed in publications P.1 (the bad environmental profile of cotton compared to synthetic fibres) and P.6 (the higher environmental burden of wool compared to acryl) of this thesis.

⁸⁸ but not for the production of hemp fibres for composites

⁸⁹ and (in line with the deliberations of Bly et al. 2015) might, or (in case of widespread acceptance and uptake) might not contribute to the sustainable 'image' of the company/brand

the DIY user might take better care of the garment or keep it in use for a longer period, but this needs to be further analysed in order to draw the right conclusion. Furthermore, as highlighted in the conclusions of P.5, the DIY product offers a more sustainable solution only if this product replaces another purchase, and not if it adds to (or even enlarges) the wardrobe the consumer would have (bought) anyway.

Derived from the envisioned example above (and also the wearable solar example from example (i) in this section), designers are advised to include these kind of 'life cycle thinking' directions (including LCSA) to support or divert from their concept design.

(vii) For the same reason as mentioned above (i.e. the hotspot is on the fibre, yarn and fabric production), designer chosen strategies to 'design out waste'⁹⁰ must be carefully considered. The designer who has this concept in mind must not overlook the fact that the zero-waste design could have implications for the quantity of fabric needed for the concept. It might be a more sustainable solution to design with less fabric *and* cut-off waste than to apply more square metres of fabric without waste. LCA could be used to underline this claim (and possibly also find a way to 'weigh' the value of the aesthetic appearance against the different environmental impacts of the several concepts; this may be achieved via the EVR method; see Mestre, 2014 and Scheepens et al. 2015).

(viii) The combination of the advantage of spun dyed modal yarn⁹¹ for knitted fabric, as described by Terinte et al. (2014), with the research of Schömers (2013) on 'True Black'⁹², could mean an incentive for designers to explore the possibilities of this technique for more sustainable solutions to create fabrics in many spectrum colours, and not only for colours with sufficiently large market volumes, i.e. for black, dark blue, brown, red and beige, as Terinte et al. (2014) describe.

Schömers (2013, p.27) suggests that the dope-dye technology offers innovation opportunities for new yarn creation (colour and/or performance) by means of varying the composition of the (different coloured) filament fibres in the yarn. In line with this idea, designers could also think of different mixes of staple fibres in the primary colours (CMYK: cyan, magenta, yellow and black) to create yarns (and fabrics) in all colours of the colour spectrum (roughly as the CMYK-colour model works for colour printing). This concept could make spin-dyeing for man-made fibres for fabrics for fashion an option⁹³, because, (a) the fabric is expected to have a better environmental profile than batch-died fabrics for fashion, and (b) the technology might overcome the barrier for companies to apply the dope-dye technology with more colours created in less time.

⁹⁰ of which many examples exist, e.g. offered in Gwilt and Rissanen (2011, p.70; p.87-95 and p.132-135)

⁹¹ in terms of environmental performance, compared with conventionally died fabric, based on LCA research, spun dye = dope dye (see Footnote 92)

⁹² True Black proposes the application of dope dye (= spun dye) as a colouration technique for man-made fibres and describes the process of colouring the polymer dope (instead of the yarn or fabric). Schömers (2013, p.24 and p.29) demonstrates the environmental advantage of this technique by means of an input-output analysis.

⁹³ which, according to Schömers (2013) is currently not the case because of the requirements of high flexibility and small batches with regards to the speed-to-market of fashion

To finalise this section on recommendations for the tranS-LCA-tor, it is important to express once more that it is (in line with the main message of this thesis) self-evident that all presented illustrations are subject to further LCSA-research and should be worked out by means of close cooperation between LCA-experts, design researchers and fashion designers (see Section 6.4).

6.6 Additional: What more can the designer do?

In the case of working independently, the designer does not need to decide on the position of the (future) employer on the CSR-ladder (as the final conclusion of Section 5.2 suggests), which would be hard and possibly even impracticable (as described in Section 6.1). It is argued that by self-becoming a social entrepreneur (C&A Foundation and Ashoka, 2016; Social enterprise monitor, 2016), the designer would be able to act more autonomously and could take much larger steps to accelerate the transformation towards a sustainable fashion system and might be more able to design 'Life Cycle Clothing' (see Section 5.2).

One step beyond this might be that designers themselves start with the development (and rapid establishment) of the fourth generation sustainable business models⁹⁴ (Melissen, 2016) and the creation of a central position for the sustainable designer within. By this means, the designer could become a sustainable entrepreneur (as a follow-up to the social entrepreneur) and might be able to bring into practice the 'sustainable development design method' (see Annex II).

⁹⁴ Melissen (2016, p.17) describes this "fourth generation" as "networked, community-oriented business models" that "ideally ... incorporate mechanisms that can truly change the rules of the game (Bocken et al. 2015)" and encourages businesses (together with "...engaged citizens, entrepreneurs, civil servants, researchers and activists...") to "...explore ways to co-create viable alternatives to our current socio-economic system - alternatives that are based on equality, inclusiveness and a responsible and sustainable way of interacting with our natural environment (Loorbach, 2014)." (Melissen, 2016, p.21)

Epilogue

When constructing the recommendations for the 'tranS-LCA-tor' in Section 6.5, I realised that I was writing this text to myself in particular.

The invention of the tranS-LCA-tor might stem from the idea that I still do not consider myself an LCSA-expert⁹⁵, but that my knowledge about LCSA and the associated language and vocabulary allow me to communicate with LCSA-experts and to interfere in the debate about LCSA of textiles. On the other hand, (although I do not consider myself as a 'hard-core'⁹⁶ designer either) I have been speaking 'design language' for over 20 years. The combination of these two factors in one person makes myself the 'perfect' tranS-LCA-tor and again underlines the observation (as described in the preface of this thesis) that "... the viewpoint of an industrial design engineer has valuable potential for [a sustainable]... fashion industry."

Although I learned an awful lot, my appetite for knowledge about the facts behind the sustainability of fashion and the possible mechanisms to change the current situation is not yet satisfied, but has become even larger. 'The more you know, the more questions arise', is only too true. At least I know better what to do next: Just follow the lines above. For me, the search towards a more sustainable fashion industry has only just begun. I hope this thesis encourages you to help me with this.

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⁹⁵ In comparison with the 'LC(S)A-community', which has already existed for more than thirty years (and the 'S-LCA community' for about ten; UNEP/SETAC, 2009), my regained experience (after my graduation project in 1994) with LCSA of only six years, leads to the conclusion that I have just entered the scene.

⁹⁶ This description is chosen to distinguish the designer, who is designing products (and product service systems), from the design manager/researcher (which better indicates my professional activities; see Biography) who guides the designer through the design-process and/or constructs the design-briefs.

References

- Afcot (2016). <http://www.afcot.org/userfiles/file/Tecnon-OrbiChem-AFCOT-Oct-2011.pdf?PHPSESSID=84751aada35e57c9373742cafa1f0c88>, accessed at 02-05-2016
- Agarwal (2010) <http://www.denimsandjeans.com/latest-denim-reports/price-structure-for-denim-jeans-in-eu/>, accessed at 23-05-2015
- Allwood, J. M., Laursen, S. E., Malvido de Rodríguez, C., & Bocken, N. M. (2006). Well dressed? The present and future sustainability of clothing and textiles in the United Kingdom. University of Cambridge
- Armstrong, C. M., Niinimäki, K., Kujala, S., Karell, E., & Lang, C. (2015). Sustainable product-service systems for clothing: exploring consumer perceptions of consumption alternatives in Finland. *Journal of Cleaner production*, 97, 30-39
- Arvidsson, R., Baumann, H., & Hildenbrand, J. (2015). On the scientific justification of the use of working hours, child labour and property rights in social life cycle assessment: three topical reviews. *The International Journal of Life Cycle Assessment*, 20(2), 161-173
- Ashby, M.F. (2015). *Materials and Sustainable Development. Exercises and Projects with worked solutions.* Cambridge UK
- Ashby, M. F., Ferrer Balas, D., Segalas Coral, J. (2015). *Materials and Sustainable Development.* Butterworth-Heinemann
- Atkinson, P. (2011). *Orchestral manoeuvres in design.* In: Abel, V. B., Klaassen, R., Evers, L. and Troxler, P. (Eds.). *Open Design Now: Why Design Cannot Remain Exclusive.* Amsterdam: BIS Publishers. <http://opendesignnow.org/index.php/article/orchestral-manoevres-in-design-paul-atkinson/>, accessed at 27-11-2015
- Ballie, J. (2012). e-co-Textile Design: Constructing a community of practice for textile design education. *The Design Journal*, 15(2), 219-236
- Benoît, C. (Ed.). (2010). *Guidelines for social life cycle assessment of products.* UNEP/Earthprint
- Beumer, G. & Koning, G. (2015). *A Speculative History of Dutch Fashion.* Het Nieuwe Instituut
- Bhardwaj, V., & Fairhurst, A. (2010). Fast fashion: response to changes in the fashion industry. *The International Review of Retail, Distribution and Consumer Research*, 20(1), 165-173
- BIPM (2015). Bureau International des Poids et Mesures. <http://www.bipm.org/en/worldwide-metrology/>, accessed at 23-13-2015
- Black, S. (2008). *Eco-chic: the fashion paradox.* Black Dog Pub Limited. London
- Bly, S., Gwozdz, W., & Reisch, L. A. (2015). Exit from the high street: an exploratory study of sustainable fashion consumption pioneers. *International Journal of Consumer Studies*, 39(2), 125-135
- Bocken, N. M. P., Rana, P., & Short, S. W. (2015). Value mapping for sustainable business thinking. *Journal of Industrial and Production Engineering*, 32(1), 67-81
- Bocken, N. M., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, 33(5), 308-320
- Borrás, S., & Edler, J. (Eds.). (2014). *The governance of socio-technical systems: explaining change.* Edward Elgar Publishing.
- Breuer, R.L. (2015). *Fashion beyond Identity. The Three Ecologies of Dress.* University of Amsterdam
- Brezet, H., van Hemel, C. (1995) *Ecodesign: a promising approach to sustainable production and consumption.* UNEP, France
- Briggs, A. (2013). Capitalism's favourite child. In: Bruzzi, S., & Gibson, P. C. (2013). *Fashion Cultures Revisited: Theories, Explorations and Analysis.* Routledge

- Brundtland, G., Khalid, M., Agnelli, S., Al-Athel, S., Chidzero, B., Fadika, L., ... & Singh, M. (1987). Our Common Future ('Brundtland report'). World Commission on Environment and Development, Oxford University Press, Oxford
- C&A Foundation and Ashoka (2016). Fabric of Change. Social entrepreneurs' perspectives that are transforming the apparel industry. Social innovation mapping
- Carbon Trust (2011). International carbon flows: Clothing. <http://www.carbontrust.com/media/38358/ctc793-international-carbon-flows-clothing.pdf>, accessed at 17-06-2016
- CCC (2013). <http://www.cleanclothes.org/issues/faq/price>, accessed at 23-05-2016
- CCC (2016). <http://www.cleanclothes.org/issues/faq-safety-accord/>, accessed at 14-01-2016
- Charter, M. & Tischner, U. (Eds.). (2001). Sustainable solutions: developing products and services for the future. Greenleaf publishing
- Claesson, A. (2006). A configurable component framework supporting platform-based product development. Chalmers University of Technology
- Cordella, M., Dodd, N., Wolf, O., & Kougoulis, J. (Eds.). (2014). Environmental Improvement Potential of textiles (IMPRO Textiles). Joint Research Center (JRC) Scientific and Policy Reports. Publications Office European Commission, Luxembourg
- Corstanje (2013). Mode als wetenschap. Elle, juli 2013, pages 86-88
- Cross, N., & Roozenburg, N. (1992). Modelling the design process in engineering and in architecture. Journal of Engineering Design, 3(4), 325-337
- Crul, M., Diehl, J. C., & Ryan, C. (2009). Design for sustainability-A step-by-step approach. UNEP, Paris
- Dahllöf, L. (2004). LCA methodology issues for textile products. Doctoral thesis. Chalmers University
- Daae, J. & Boks, C. (2015) Opportunities and challenges for addressing variations in the use phase with LCA and Design for Sustainable Behaviour. International Journal of Sustainable Engineering. Volume 8, Issue 3, May 2015, pages 148-162
- De Clercq, S., 2008. Towards sustainable business uniforms. Master thesis (master). Delft University of Technology
- De Man, R., Brezet, J.C. (2016). Wieg tot Wieg is utopie. Tijdschrift Milieu, maart 2016, 8-10
- De Pauw, I. C. (2015). Nature-Inspired Design: Strategies for Sustainable Product Development. Doctoral thesis. Delft University of Technology
- De Waart, S., Heuvelings, M., Meerendonk, H., Lordkipanze, M., Tischner, U., Rams, N., Markowska, K., Andziak, Z., Van der Velden, N.M. (2009). Green Fashion Project Pre-IPC study End Report. Material Sense, Cartesius Institute, Econcept, VanMarkoviec, Delft University of Technology
- Delft Design Guide (2015). http://www.slideshare.net/DelftOpenEr/Ecodesign-strategy-wheel?qid=eebe4ae3-616a-4bfd-937c-38021d84175e&v=default&b=&from_search=1, accessed at 16-12-2015
- Deleuze, G., & Guattari, F. (2014). What is philosophy? Columbia University Press
- DuPont USA (2012). Patel, M.K., Geldof, M., Van der Velden, N.M., Vogtländer J.G., Kurian, J.V., Veith, S. (2012). Environmental assessment of selected Sorona© fibre products, commissioned by DuPont, Wilmington, DE 19880, USA
- EC (2013). http://ec.europa.eu/growth/sectors/fashion/textiles-clothing/eu/index_en.htm, accessed at 01-06-2016
- ECHA (2011). http://echa.europa.eu/documents/10162/13638/agreement_dmac_20111124_en.pdf, accessed at 06-05-2016
- Ecoinvent (2010). Database Ecoinvent version V2.2, The Swiss Centre for Life Cycle Inventories
- Ecoinvent (2014). Database Ecoinvent Version V3.01, The Swiss Centre for Life Cycle Inventories
- Ecolizer (2016). <http://www.ecolizer.be/>, accessed at 18-01-2016

- EenVandaag (2016). http://www.npo.nl/eenvandaag/09-04-2016/AT_2047512, accessed at 10-04-2016
- Ehrenfeld, J. (2008). *Sustainability by design. A subversive strategy for transforming our consumer culture*. New Haven: Yale University
- Ellen MacArthur (2010). <http://www.ellenmacarthurfoundation.org/about/history>, accessed at 13-01-2016
- Elkington, J., Trisoglio, A. (1996). Developing realistic scenarios for the environment: Lessons from Brent Spar. *Long Range Planning*, 29(6), 762-769
- Entwistle, J. (2000). *The Fashioned Body. Fashion, Dress and Modern Social Theory*. Polity Press, Cambridge
- EU (2009). DIRECTIVE 2009/125/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 21 October 2009
- EU (2010). ILCD handbook. Framework and requirements for life cycle impact assessment models and indicators; Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment; Recommendations based on existing environmental impact assessment models and factors for Life Cycle Assessment in a European context. Publications Office of the European Union, European Commission - Joint Research Centre. Luxembourg
- EU Ecolabel (2016). <http://ec.europa.eu/environment/ecolabel/the-ecolabel-scheme.html>, accessed at 10-06-2016
- EVR (2015). <http://www.ecocostsvalue.com/>, accessed at 17-12-2015
- Farrer, J. (2011). Remediation: Discussing fashion textiles sustainability. In: Gwilt, A., & Rissanen, T. (2011). *Shaping sustainable fashion: Changing the way we make and use clothes*. Routledge, p. 19-33.
- Fletcher, K. (2008). *Sustainable fashion & textiles: Design journeys*. Earthscan, London
- Fletcher, K. (2010). Slow fashion: an invitation for systems change. *Fashion Practice*, 2(2), 259-265
- Fletcher, K. (2012). Durability, fashion, sustainability: the processes and practices of use. *Fashion practice*, 4(2), 221-238
- Fuad-Luke, A. (2002). 'Slow Design' – A paradigm shift in design philosophy? Development by Design, dyd02. Bangalore, India. Alastair Fuad Luke and Thinkcycle
- Future Fashion Manifesto (2015). *Mistra Future Fashion*. Mistra, the Swedish Foundation for Strategic Environmental Research
- Gardetti, M. A., & Torres, A. L. (Eds.). (2013). *Sustainability in fashion and textiles: values, design, production and consumption*. Greenleaf Publishing
- Gausemeier, I. J. (2011). *Thinking ahead the Future of Additive Manufacturing–. Analysis of Promising Industries*, Heinz Nixdorf Institute, University of Paderborn Product Engineering, Paderborn, 14
- GOTS (2014). Global organic textile standard. <http://www.global-standard.org/the-standard/general-description.html>, accessed at 10-06-2016
- Guardian (2015). <http://labs.theguardian.com/unicef-child-labour/>, accessed at 13-01-2016
- Guinée, J. B. (2002). Handbook on life cycle assessment operational guide to the ISO standards. *The international journal of life cycle assessment*, 7(5), 311-313
- Guinée, J. B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., ... & Rydberg, T. (2011). Life cycle assessment: past, present, and future†. *Environmental science & technology*, 45(1), 90-96
- Greenpeace (2016). Detox campaign, ongoing since 2011. <http://www.greenpeace.org/international/en/campaigns/detox/fashion/>, accessed at 14-01-2016
- Gwilt, A., & Rissanen, T. (2011). *Shaping sustainable fashion: Changing the way we make and use clothes*. Routledge
- Hawley, J. M. (2006). Digging for diamonds: A conceptual framework for understanding reclaimed textile products. *Clothing and Textiles Research Journal*, 24(3), 262-275

- Hekkert, P., Mostert, M., & Stompff, G. (2003, June). Dancing with a machine: a case of experience-driven design. In *Proceedings of the 2003 international conference on Designing pleasurable products and interfaces* (pp. 114-119). ACM
- Herva, M., Álvarez, A., & Roca, E. (2012). Combined application of energy and material flow analysis and ecological footprint for the environmental evaluation of a tailoring factory. *Journal of hazardous materials*, 237, 231-239.
- Higg Index (2012). <http://apparelcoalition.org/our-origins/>, accessed at 18-01-2016
- Huisman, J. (2003). The QWERTY/EE concept, quantifying recyclability and eco-efficiency for end-of-life treatment of consumer electronic products. Doctoral thesis. Delft University of Technology
- Idemat (2012). Database Idemat version 2012, Delft University of Technology. Available at <http://www.ecocostsvalue.com/EVR/model/theory/subject/5-data.html>
- Idemat (2014). Database Idemat version 2014, Delft University of Technology, 2014. Available at <http://www.ecocostsvalue.com/EVR/model/theory/subject/5-data.html>
- ILO (2014) Wages and Working Hours in the Textiles, Clothing, Leather and Footwear Industries. International Labour Office, Genève, Switzerland
- ISO 14040 (2006) Environmental Management - Life cycle assessment - Principles and Framework. ISO/FDIS. Geneva, Switzerland
- ISO 14044 (2006) Environmental Management - Life cycle assessment - Principles and Framework. ISO/FDIS. Geneva, Switzerland
- Jackson, T. & Shaw, D. (2009) *Mastering fashion marketing*. Palgrave McMillan
- Johansson, A., Kisch, P., & Mirata, M. (2005). Distributed economies—a new engine for innovation. *Journal of Cleaner Production*, 13(10), 971-979
- Joore, P., & Brezet, H. (2015). A Multilevel Design Model: the mutual relationship between product-service system development and societal change processes. *Journal of Cleaner Production*, 97, 92-105
- Kaiser, S. (1990). *The Social Psychology of Clothing: Symbolic Appearances in Context*. 2nd edition. Macmillan, New York
- Karana, E., Barati, B., Rognoli, V., & Zeeuw van der Laan, A. (2015). Material driven design (MDD): A method to design for material experiences. *International journal of design*, 19 (2) 2015
- Kawamura, Y. (2005). *Fashion-ology: an introduction to fashion studies*. Berg, New York
- Kogg, B. (2009). *Responsibility in the Supply Chain: Interorganisational management of environmental and social aspects in the supply chain-Case studies from the textile sector*. Lund University
- Köhler, A. R. (2013). *Anticipatory Ecodesign Strategies for Smart Textiles. Perspectives on environmental risk prevention in the development of an emerging technology*. Doctoral thesis. Delft University of Technology
- Koning, H. H. (2013). *The Influence of Yarn Count on the Electricity Consumption of Spinning and Weaving Machines*. University College Utrecht
- Köppchen, A. (2014). *Mind the Gap. Balancing design and global manufacturing in Dutch fashion*. Doctoral thesis. Radboud University Nijmegen
- Kuusk, K. (2016). *Crafting sustainable smart textile services*. Doctoral thesis. Eindhoven University of Technology
- Larsson, A., Buhr, K., Mark-Herbert, C. (2013) Corporate responsibility in the garment industry. Towards shared value. In: Gardetti, M. A., & Torres, A. L. (Eds.). (2013). *Sustainability in fashion and textiles: values, design, production and consumption*. Greenleaf Publishing
- Lantor NL (2013). Van der Velden, N.M. (2013) *Life Cycle Assessment of CondenStop CS*, commissioned by Lantor, Veenendaal
- Laterveer, M. (2015) Zo dun is het duurzame laagje van de mode-industrie. *Vrij Nederland*, 10 december 2015

- Laitala, K., Boks, C., & Klepp, I. G. (2015). Making clothing last: A design approach for reducing the environmental impacts. *International Journal of Design*, 9(2), 93-107.
<http://www.ijdesign.org/ojs/index.php/IJDesign/article/view/1613/696>, accessed at 17-06-2016
- LCAatogo (2011). Boosting Life Cycle Assessment Use in European Small and Medium-sized Enterprises. Technical Report on Needs and Demands of SMEs, <http://www.lca2go.eu/results.en.html>, accessed at 31-05-2016
- LCAatogo (2013). Deliverable D4.2 Scientific Case Study Reports and Evaluations, ILCD datasets, <http://www.lca2go.eu/results.en.html>, accessed at 31-05-2016
- LCAatogo (2016). Smart Textiles Case Studies <http://www.lca2go.eu/sectors,textile.en.html>, accessed at 31-05-2016
- Leiden-Erasmus-Delft (2016). <http://www.leiden-delft-erasmus.nl/en/education/masters-programmes-and-tracks>, accessed at 22-09-2016
- Levy-Bruhl, L. (1966). *The Soul of the Primitive*. George Allen and Unwin. London
- Lindahl, M., & Ekermann, S. (2013). Structure for categorization of ecodesign methods and tools. In *Re-engineering Manufacturing for Sustainability* (pp. 117-122). Springer Singapore
- Lofthouse, V. A., (2001). *Facilitating Ecodesign in an Industrial Design Context: An Exploratory Study*. Doctoral thesis. Cranfield University, Cranfield, UK
- Lofthouse, V. (2006). Ecodesign tools for designers: defining the requirements. *Journal of Cleaner Production*, 14(15), 1386-1395
- Loorbach, D. (2014). *To Transition! Governance Panarchy in the New Transformation*. inaugural address. Rotterdam: DRIFT-Erasmus University Rotterdam
- Lussenburg, K. M. (2014). *Designing [with] 3D Printed Textiles, a material driven design project*. Master thesis. Delft University of Technology
- Luttropp, C., Lagerstedt, J. (2006). Ecodesign and The Ten Golden Rules: generic advice for merging environmental aspects into product development. *Journal of Cleaner Production*, 14(15), 1396-1408
- MacLeans (2013) <http://www.macleans.ca/economy/business/what-does-that-14-shirt-really-cost/>, accessed at 23-05-2016
- Made-by Brand Tools & Benchmarks (2016). <http://www.made-by.org/consultancy/tools/>, accessed at 18-01-2016 and <http://www.made-by.org/modetracker/about/>, accessed at 4-4-2016
- Madsen, J., Hartlin, B., Perumalpillai, S., Selby, S. and Aumônier, S. (2007). *Mapping of Evidence on Sustainable Development Impacts that Occur in Life Cycles of Clothing: A Report to the Department for Environment, Food and Rural Affairs*. Environmental Resources Management (ERM) Ltd. Defra, London
- Maldini, I. (2016). Attachment, Durability and the Environmental Impact of Digital DIY. *The Design Journal*, 19(1), 141-157
- Manda, B. K., Worrell, E., & Patel, M. K. (2015). Prospective life cycle assessment of an antibacterial T-shirt and supporting business decisions to create value. *Resources, Conservation and Recycling*, 103, 47-57
- Manda, B. K., Bosch, H., Karanam, S., Beers, H., Bosman, H., Rietveld, E., Worrel, E. & Patel, M. K. (2016). Value creation with life cycle assessment: an approach to contextualize the application of life cycle assessment in chemical companies to create sustainable value. *Journal of Cleaner Production*, 126, 337-351
- Manzini, E. (1999). Strategic design for sustainability: towards a new mix of products and services. In *Environmentally Conscious Design and Inverse Manufacturing*, 1999. Proceedings. Ecodesign'99: First International Symposium On (pp. 434-437). IEEE
- Manzini, E. (2009). View point. *New design knowledge*. *Design Studies*, 30, 4-12
- Mawle, R., Bhamra, T., & Lofthouse, V. (2010). *The practice of ecodesign: A study of small product design consultancies*. Knowledge Collaboration & Learning for Sustainable Innovation ERSCP-EMSU conference, Delft, The Netherlands, October 25-29, 2010

- Melissen (2016). 4th Generation sustainable business models. Inaugural speech March 1 2016. NHTV Breda University of Applied sciences. <http://www.hospitalityatwork.nl/wp-content/uploads/Inaugural-speech-FM.pdf>, accessed at 14-06-2016
- Mestre, A. C. C. M. (2014). Cork Design: A Design Action Intervention Approach Towards Sustainable Product Innovation. Doctoral thesis. Delft University of Technology
- Meursing, M (2015a) <http://idematapp.com/#home>, accessed at 24-05-2016
- Meursing, M. (2015b). Sustainability Inspired Materials Selection App for Designers. Master thesis. Delft University of Technology
- McCracken, G. (1990). Culture and Consumption. A New Approach to the Symbolic Character of Consumer Goods and Activities. 2nd edition. Indiana University Press, Bloomington
- McKinsey (2016). <http://www.mckinsey.com/industries/retail/our-insights/east-africa-the-next-hub-for-apparel-sourcing>, accessed at 02-05-2016
- Miller, D. (1992) Material Culture and Mass Consumption. 4th edition. Blackwell, Oxford
- Modint Ecotool (2012). http://avnir.org/documentation/book/LCAconf_bijleveld1_2012_en.pdf, accessed at 18-01-2016
- Morgan, A. (2015). <http://truecostmovie.com/>, accessed at 14-01-2016
- Muthu, S. S., Li, Y., Hu, J. Y., & Mok, P. Y. (2012). Recyclability Potential Index (RPI): The concept and quantification of RPI for textile fibres. *Ecological Indicators*, 18, 58-62
- Niinimäki, K. (2011). From disposable to sustainable: the complex interplay between design and consumption of textiles and clothing. Aalto University
- Niinimäki, K., & Hassi, L. (2011). Emerging design strategies in sustainable production and consumption of textiles and clothing. *Journal of Cleaner Production*, 19(16), 1876-1883
- Niinimäki, K., & Koskinen, I. (2011). I love this dress, it makes me feel beautiful! Empathic knowledge in sustainable design. *The Design Journal*, 14(2), 165-186
- Niinimäki, K. (2013). Sustainable fashion: new approaches. Aalto University
- Nike Making app (2013) <http://news.nike.com/news/nike-unveils-new-app-to-help-designers-invent-better> and <http://www.theguardian.com/sustainable-business/nike-making-app-sustainability-design>, accessed at 18-01-2016
- OEKO-TEX® (2016). https://www.oeko-tex.com/en/business/certifications_and_services/certifications_and_services.html, accessed at 10-06-2016
- Pan, Y., Roedel, D., Blevis, E., & Thomas, J. (2015). Fashion thinking: Fashion practices and sustainable interaction design. *International Journal of Design*, 9(1)
- Pedersen, K., Emblemståg, J., Bailey, R., Allen, J. K., Mistree, F. (2000). Validating Design Methods & Research: The Validation Square. Proceedings of DETC'00, 2000 ASME Design Engineering Technical Conferences, September 10-14, 2000, Baltimore, Maryland
- Petala, E., Wever, R., Dutilh, C., & Brezet, H. (2010). The role of new product development briefs in implementing sustainability: A case study. *Journal of Engineering and Technology Management*, 27(3), 172-182
- Poldner, K. (2011) Zigzag or interlock? The case of the Sustainable Apparel Coalition. In: Gwilt, A., & Rissanen, T. (2011). *Shaping sustainable fashion: Changing the way we make and use clothes*. Routledge
- Ramani, K., Ramanujan, D., Bernstein, W. Z., Zhao, F., Sutherland, J., Handwerker, C., ... & Thurston, D. (2010). Integrated sustainable life cycle design: a review. *Journal of Mechanical Design*, 132(9), 091004
- Ramus, C. A., & Montiel, I. (2005). When are corporate environmental policies a form of greenwashing?. *Business & Society*, 44(4), 377-414
- Rana Plaza (2013). <http://www.cleanclothes.org/ranaplaza>. Clean Clothes Campaign, accessed at 14-01-2016

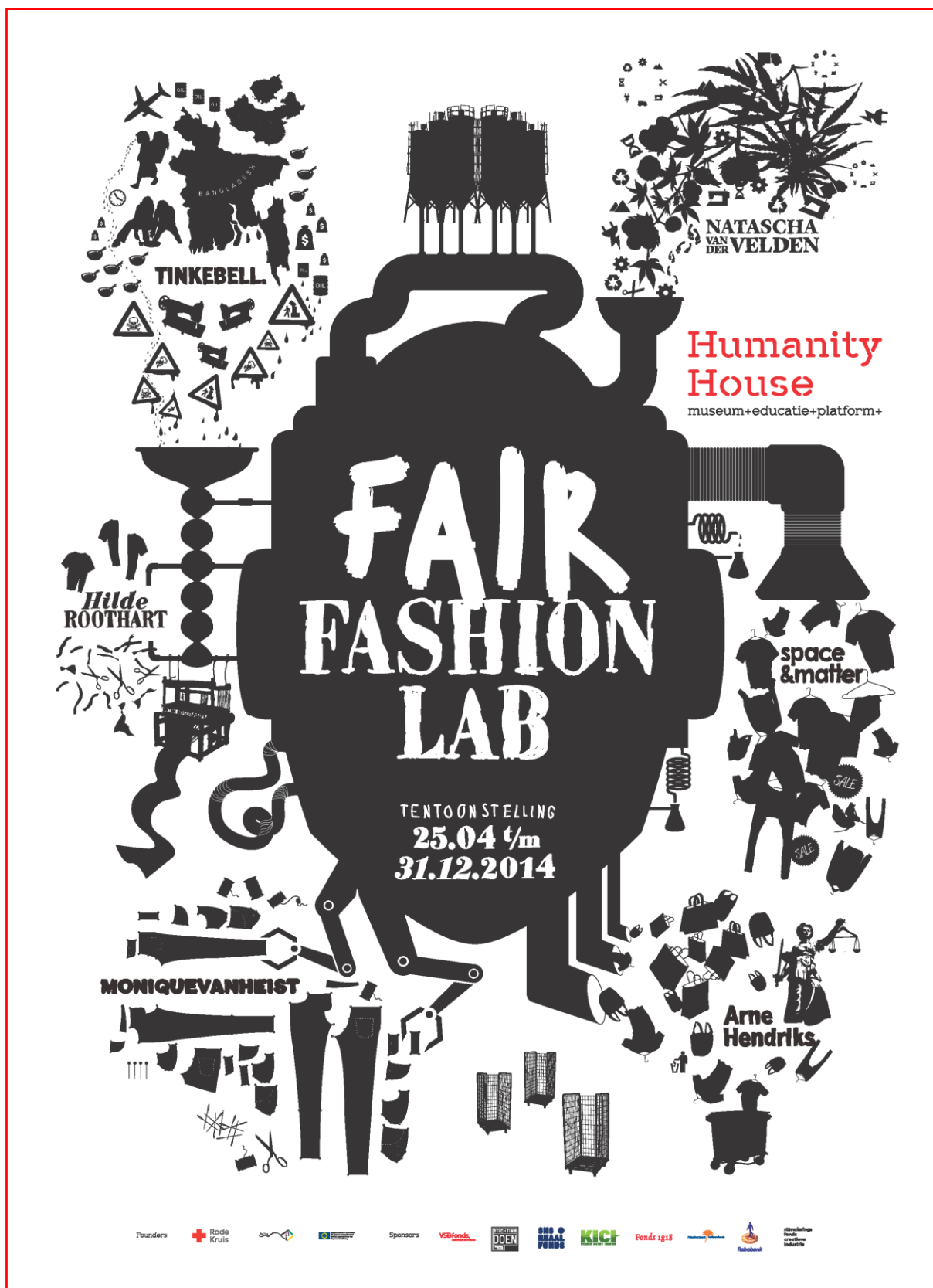
- Reymen, I. (2001). Improving design processes through structured reflection: A domain-independent approach. Doctoral thesis. Eindhoven University of Technology.
- Righton, N. (2016). Lijst met eerlijke kledingmerken. Volkskrant 04-07-2016, p.1
- Rivas-Hermann, R., Köhler, J., & Scheepens, A. E. (2015). Innovation in product and services in the shipping retrofit industry: a case study of ballast water treatment systems. *Journal of Cleaner Production*, 106, 443-454
- Rocamora, A., & Smelik, A. (2016). *Thinking Through Fashion. A Guide to Key Theorists*. I.B. TAURIS, London – New York
- Roos, S., Zamani, B., Sandin, G., Peters, G. M., & Svanström, M. (2016). An LCA-based approach to guiding an industry sector towards sustainability: the case of the Swedish apparel sector. *Journal of Cleaner Production*, 133 (2016), 691-700
- Røyne, F., Peñaloza, D., Sandin, G., Berlin, J., & Svanström, M. (2016). Climate impact assessment in life cycle assessments of forest products: Implications of method choice for results and decision-making. *Journal of Cleaner Production* (in press)
- Ruebens (2016) http://www.rhizomedesign.co.in/view_project_detail.php?id=161, accessed at 14-05-2016
- SAC Tools (2016). <http://apparelcoalition.org/product-tools/>, accessed at 18-01-2016
- Sahni, H., Khan, B. M., & Barad, K. (2015). Analyzing Customer Experience Constructs that Induce Apparel Product Attachment in Young Consumers. *International Journal of Applied Sciences and Management (IJASM)*, Vol. 1, no. 1, 12-27
- Sakao, T. (2015) *Eco-Co-design – Ecodesign with Communication, Cooperation, and Co-creation: A preliminary report*. GCPC2015, Sitges. Spain
- Savaskan, R. C. (2013). *Building a better Cittaslow: Bringing the Slow City to its Inhabitants*. Master Thesis Delft University of Technology
- Schau, E. M., Traverso, M., & Finkbeiner, M. (2012). Life cycle approach to sustainability assessment: a case study of remanufactured alternators. *Journal of Remanufacturing*, 2(1), 1-14
- Scheepens, A. E., Vogtländer, J. G., & Brezet, J. C. (2015). Two life cycle assessment (LCA) based methods to analyse and design complex (regional) circular economy systems. Case: Making water tourism more sustainable. *Journal of Cleaner Production*
- Schömers, S. F. (2013). *TRUE BLACK: driving performance with the environment*. Master thesis. Delft University of Technology
- Schön, D.A. (1983). *The reflective practitioner*. Basic Books, New York
- SER (2016) *Convenant Duurzame Kleding en Textiel*. Sociaal Economische Raad of the Netherlands
- Shen, L. (2011). *Bio-based and recycled polymers for cleaner production: an assessment of plastics and fibres*. Utrecht University
- Shove, E., Watson, M., Hand, M., & Ingram, J. (2014). The Design of Everyday Life. *Technoscienza*, 5(2), 33-42
- SKC (2014). *Loon naar werken. Wat kledingmerken doen (en laten) voor een leefbaar loon*. Schone kleren Campagne
- SKC (2016). <http://www.schonekleren.nl/informatie/faq/zijn-schone-kleren-duurder>, accessed at 23-05-2016
- Smink, M. M. (2015). *Incumbents and institutions in sustainability transitions*. Doctoral thesis. Utrecht University
- Social enterprise monitor (2016). https://www.social-enterprise.nl/files/6814/6425/0554/Social_Enterprise_Monitor_2016.pdf, accessed at 14-06-2016
- Spangenberg, J. H., Fuad-Luke, A., & Blincoe, K. (2010). Design for Sustainability (DfS): the interface of sustainable production and consumption. *Journal of Cleaner Production*, 18(15), 1485-1493
- Stam, C. J. (2016). *Locally go from digital to garments*. Master thesis. Delft University of Technology

- Statista (2016). <http://www.statista.com/statistics/263055/cotton-production-worldwide-by-top-countries/>, accessed at 02-05-2016
- Stotz, L., & Gillian, K. (2015) Facts on the Global Garment Industry. Clean Clothes Campaign. 1 Feb. 2015. <http://www.cleanclothes.org/resources/publications/factsheets/general-factsheet-garment-industry-february-2015.pdf>, accessed at 18-03-2016
- Sweeny, G. (2015). <http://ecowatch.com/2015/08/17/fast-fashion-second-dirtiest-industry/>, accessed at 18-03-2016
- TE (2016) TextileExchange Material Summaries and Material Snapshots
<http://textileexch.wpengine.com/publications/#material-summaries> and
<http://textileexch.wpengine.com/publications/#material-snapshots>, accessed at 29-01-2016
- Terinte, N., Manda, B. M. K., Taylor, J., Schuster, K. C., & Patel, M. K. (2014). Environmental assessment of coloured fabrics and opportunities for value creation: spin-dyeing versus conventional dyeing of modal fabrics. *Journal of cleaner production*, 72, 127-138
- The TEN (2016). <http://www.tedresearch.net/teds-ten/>, accessed at 18-01-2016
- Tischner, U. & Charter, M., (Eds.). (2001). *Sustainable solutions: developing products and services for the future*. Greenleaf publishing
- Toeters, M., ten Bhömer, M., Bottenberg, E., Tomico, O., & Brinks, G. (2013, January). Research through design: a way to drive innovative solutions in the field of smart textiles. In *Advances in Science and Technology*, Vol. 80, pp. 112-117
- Tokatli, N., Wrigley, N., & Kizilgün, Ö. (2008). Shifting global supply networks and fast fashion: made in Turkey for Marks & Spencer. *Global Networks*, 8(3), 261-280
- Tsao, C. C., & Plepys, A. (2008). Applying IO Approaches for Estimating Environmental Impacts of Industry and Policy in a Life Cycle Perspective. Master thesis. Lund University
- UN (2015) <http://www.un.org/sustainabledevelopment/development-agenda/#>, accessed at 07-12-2015
- UNEP/SETAC (2009) Guidelines for Social Life Cycle Assessment of Products. Available at:
http://www.unep.org/pdf/DTIE_PDFS/DTI1x1164xPA-guidelines_sLCA.pdf
- UNEP/SETAC (2011) Towards a Life Cycle Sustainability Assessment. Available at:
http://www.unep.org/pdf/UNEP_LifecycleInit_Dec_FINAL.pdf
- Valdivia, S., Ugaya, C. M., Hildenbrand, J., Traverso, M., Mazijn, B., & Sonnemann, G. (2011). Towards a Life Cycle Sustainability Assessment. Making informed choices on products. UNEP/SETAC Life Cycle Initiative
- Valdivia, S., Ugaya, C. M., Hildenbrand, J., Traverso, M., Mazijn, B., & Sonnemann, G. (2013). A UNEP/SETAC approach towards a life cycle sustainability assessment—our contribution to Rio+ 20. *The International Journal of Life Cycle Assessment*, 18(9), 1673-1685
- Van Bommel, H.W.M. (2016) Sustainability Strategies in Industrial Supply Networks: An innovation approach concerning environmental and social aspects in the clothing industry. Doctoral thesis. University of Twente. The Netherlands
- Van Berkel, S. (2016). Fair Factory to Happy Factory. Research and design for safe and healthy textile factories in Bangladesh. MSc. graduation project. Faculty of Architecture, Delft University of Technology
- Van der Keuken, T. (2015) <http://www.vpro.nl/buitenland/programmas/slag-om-de-klerewereld/Ondoorzichtige-kleding.html>, accessed at 14-01-2016
- Van der Lugt, P., & Vogtländer, J. G. (2014). Wood acetylation: a potential route towards climate change mitigation. *Eco-Architecture V: Harmonisation between Architecture and Nature*, 142, 241
- Van der Velden, N.M. (1994). Klere(n)milieu. Milieu-aspecten van kleding. Graduation thesis. Delft University of Technology. Delft, The Netherlands
- Van Dongen, P. (2013). <http://paulinevandongen.nl/projects/wearable-solar/>, accessed at 14-01-2016

- Van Eynde, H. (2015). Comparative Life Cycle Assessment of hemp and cotton fibres used in Chinese textile manufacturing. Master thesis. KU Leuven
- Van Herpen, I. (2013) http://www.irisvanherpen.com/_uploaded/Voltage.pdf, accessed at 14-01-2016
- Vogtländer, J. G., Mestre, A., van der Helm, R., Scheepens, A., Wever, R. (2013). Eco-efficient value creation, sustainable design and business strategies. Sustainable Design Series of Delft University of Technology, VSSD, Delft
- Vogtländer, J.G. (2016) A practical guide to LCA for students, designers and business managers, Cradle-to-Grave and Cradle-to-Cradle, 4th edition 2016. Sustainable Design Series of Delft University of Technology, VSSD, Delft
- Von Busch, O. (2010). 'Re-examining the politics of design'. XXI Magazine, 92, September 2010. <http://selfpassage.org/XXI/XXI-1004/1004.htm>, accessed at 25-05-2016
- Vuletich (2010) In: Earley, R., Goldsworthy, K., & Vuletich, C. (2010). Textiles, environment, design (TED): Making theory into textiles through sustainable design strategies, pedagogy and collaboration. Future Textile Environments. http://www.tedresearch.net/media/files/TED_Making_Theory_into_Textiles_2010.pdf, accessed at 30-11-2015
- Wang, Y. (Ed.). (2006). Recycling in textiles. Woodhead publishing
- WBCSD (2005) Eco-efficiency learning module. World Business Council for Sustainable Development, FiveWinds International
- WBCSD (2016) <http://www.wbcd.org/pages/EDocument/EDocumentDetails.aspx?ID=13593>, accessed at 4-4-2016
- Weller, I. (2013). Sustainable consumption and production patterns in the clothing sector. In: Gardetti, M. A., & Torres, A. L. (Eds.). (2013). Sustainability in fashion and textiles: values, design, production and consumption. Greenleaf Publishing
- Wever, R., Van Kuijk J., Boks, C. (2008). User-centred design for sustainable behaviour. International Journal of Sustainable Engineering. Volume 1, Issue 1, March 2008, pages 9-20
- WTO (2014) World Trade Organization International Trade Statistics 2014 https://www.wto.org/english/res_e/statis_e/its2014_e/its14_highlights2_e.pdf, accessed at 17-03-2016
- Yacout, D. M., El-Kawi, M. A., & Hassouna, M. S. (2016). Cradle to gate environmental impact assessment of acrylic fiber manufacturing. The International Journal of Life Cycle Assessment, 1-11
- Zhang, Y., Liu, X., Xiao, R., & Yuan, Z. (2015). Life cycle assessment of cotton T-shirts in China. The International Journal of Life Cycle Assessment, 1-11. Zhang, Y., Liu, X., Xiao, R., & Yuan, Z. (2015). Life cycle assessment of cotton T-shirts in China. The International Journal of Life Cycle Assessment, 1-11

Annex I

A1. Exhibition Fair Fashion Lab Humanity House



In the year 2014, the author was asked to contribute to an exhibition named *Fair Fashion Lab*, which ran from April 24th until January 2015, in the Humanity House museum (www.humanityhouse.org) in The Hague.

With this exhibition, the makers expressly wanted to enter into dialogue with the garment industry, with policy makers, and with the public. To do so, they asked designers, artists and researchers⁹⁷ to present their vision in the form of an installation.



Fig. A1 First sketch for the pocket at the Fair Made Fashion Lab (by Frank Bleeker)

In the pocket *Life Cycle Clothing* (see Figures A1 and A2), the ecodesign strategy wheel (= the LiDS wheel, as presented in Section 2.3.3) was introduced as a method to provide insight into environmental aspects of clothing products. Together with industrial design engineering (IDE) graduate student Kirsten Lussenburg, the author showed the public how the ecodesign strategy wheel is applied in research into future solutions, from 3D printing and clothing made from elephant grass (*Miscanthus*) to the idea that we should all swallow a hair growth pill so that we no longer need clothing.

⁹⁷ Monique van Heist, Arne Hendriks, Hilde Roothart, space&matter (Sascha Glasl, Tjeerd Haccou, Frederica Heimler), TINKEBELL and me in cooperation with Rivet Concept Development of Jemma Land.

Over 8,000 people visited the exhibition and side programme with festivals, workshops and lectures (see <http://www.humanityhouse.org/over-ons/jaarverslag/> and Figure A3).

Fair Fashion Lab yielded substantial media attention; among others in the broadcast of the Dutch daily news Nieuwsuur (<http://nieuwsuur.nl/video/639045-een-jaar-na-rana-plaza-bangladesh.html>) and well-known newspapers, see next pages, figures A4-A6). In total, for a PR-value of €250,000, as estimated by the museum.



Fig. A2 Impression of the installation 'Life Cycle Clothing'



Fig. A3a-b Minister Ploumen of Foreign Trade and Development Cooperation opens Fair Fashion Lab on April 24th, 2014 (photo (a) left by Rebke Klokke/Humanity House) and the author gives a lecture (b).

V18 DE VOLKSKRANT
VRIJDAG 25 APRIL 2014

BEWUSTWORDING FAIR FASHION LAB

Duurzame kleren naai je zelf

Lisa Koetsenruijter
Amsterdam

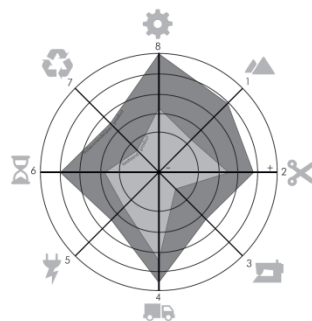
Een pil nemen om je haar zo lang te laten groeien dat je geen kleren meer hoeft te dragen: de ultieme oplossing voor een eerlijke kledingindustrie volgens onderzoeker Natascha van der Velden. Dan hoeven we immers niets meer te verbouwen en niemand meer te laten werken voor onze kleding. Ze presenteert het 'discussie-idee' op de tentoonstelling Fair Fashion Lab, die tot het eind van het jaar te bezoeken is in Den Haag.

ADVERTENTIE

**De
prooi**

het
**Nationale
Toneel**

**Mark
Rietman
is
Rijkman
Groenink**



Een jaar na de ramp in Bangladesh presenteert het Humanity House vijf visies op een eerlijke kledingindustrie. De wetenschappelijke insteek komt van Van der Velden. Ze promoveert aan de TU Delft op duurzame kledingproductie en laat bezoekers kennismaken met het EcoDesign Strategy Wheel (zie afbeelding): een soort spinnenweb met acht assen die de duurzaamheid van diverse aspecten van een product meten. Van der Velden: 'Hoe groter het oppervlak, hoe beter je bezig bent.'

Ze wil in haar wiel zoveel mogelijk factoren verwerken. 'Er zijn al honderden labels, maar die gaan steeds over maar een klein stukje van de productie. Dat het katoen biologisch is bijvoor-

beeld. Ik wil het geheel vatten in één cijfer.' Nu bestrijkt het wiel acht factoren die gaan over de impact op de aarde, zoals materiaalkeuze, productieproces en distributie.

Op de tentoonstelling is het wiel verwerkt als duurzaamheidslabel aan een stukje stof van olifantengras, een gewas dat ook in Nederland kan groeien en minder water behoeft dan katoen. Toch was een kledinglabel niet de eerste toepassing die Van der Velden had bedacht. 'Het is een tool voor productontwerpers, ze kunnen zien met welke factoren ze rekening moeten houden. Dit slaat aan bij het grote publiek, het is makkelijk te snappen. Het was niet de intentie, maar we zouden zo'n label best in het leven kunnen roepen.'

Naast Van der Velden tonen ook kunstenaars Tinkebell en Arne Hendriks, trendwatcher Hilde Roothart en modeontwerper Monique van Heist hun visie op de kledingindustrie. Die laatste stelde haar protestcoat beschikbaar. Bezoekers kunnen hem passen en dan van de juiste maat het 23-delige patroon overtekenen en het thuis zelf naaien. Een klus om even goed voor te gaan zitten – net zoals ze doen in de kledingfabrieken.

Fig. A4 Article in De Volkskrant (250,000 copies), Friday 25th April 2014, p.V18

www.spitsnieuws.nl

donderdag
24 april 2014**SP!TS**

Er is reden tot hoop



Wie, wat, waar ook alweer?

Op 24 april 2013, om 09:00 uur 's ochtends, stortte Rana Plaza in. Op dat moment waren er 3122 mensen aanwezig in het gebouw waar eerder al grof achterstallig onderhoud was geconstateerd. In het gebouw werd kleding voor onder meer Benetton, Mango, Primark en Walmart gefabriceerd, ook al was de locatie oorspronkelijk bedoeld en gebouwd voor winkels en kantoren, niet om dienst te doen als fabriek. De muren konden de trillingen van de machines niet aan. Meer dan 1000 mensen kwamen om het leven en ruim 2000 mensen raakten gewond. De instorting geldt als de dodelijkste ramp ooit in een textielfabriek. FOTO: EPA

Fig. A5a Article in Sp!ts (267,000 copies), Thursday 24th April 2014, p.2

Het is vandaag een jaar geleden dat de ramp met de Bengaalse kledingfabriek plaatsvond. Spits sprak met trendanalist Lynsey Dubbeld, onderzoeker Natascha van der Velden van de TU Delft en Christa de Bruin van de Schone Kleren Campagne over wat er sindsdien is veranderd.

DOOR SIGRID STAMKOT

Wat is er sinds 24 april 2013 gebeurd?

Lynsey: „Er is veel belangstelling voor de kledingindustrie in Bangladesh ontstaan. Dat kan de situatie in Bangladesh aanzienlijk verbeteren en tegelijkertijd het enthousiasme onder modeliefhebbers voor duurzame labels vergroten.”

Natascha: „Er is een schokgolf door de hele industrie gegaan, die heeft gezorgd voor meer kennis bij de consument. Daarnaast hebben overheden druk gelegd op goede regels. Er is dus zeker iets gaande, maar wat er daadwerkelijk is gebeurd, dat is moeilijk te peilen en dat maakt het zo lastig. Het publiek is in de war door de misleidende informatie en weet niet zo goed hoe die info te beoordelen.”

Christa: „Sinds die tijd weet iedereen dat veel kleding gemaakt wordt in onveilige fabrieken met slechte arbeidsomstandigheden. In één klap werd duidelijk dat er snel actie nodig is om de levensbedreigende fabrieken en de arbeidsomstandigheden van de miljoenen kledingarbeiders in Bangladesh en andere landen aan te pakken en te verbeteren.”

Waar staan we nu?

Lynsey: „Er zijn veel initiatieven genomen om de textielsector in Bangladesh eerlijker te maken. Zoals bijvoorbeeld het Accord on Fire and Building Safety in Bangladesh. Daarmee hebben onder meer De Bijenkorf, HEMA, H&M en WE Fashion de toezegging gedaan om samen met fabrieken en vakbonden in Bangladesh te werken aan verbetering van de veiligheid bij hun producenten. De overheid van Bangladesh heeft het wettelijke minimumloon voor werknemers in de kledingsector verhoogd: van ongeveer 30 euro naar ongeveer 50 euro per maand. Maar vooral: het bewustzijn onder consumenten van de (on)duurzaamheid van de mode in onze winkelstraten is aanzienlijk vergroot. Vooral de media-aandacht heeft er toe geleid dat steeds meer modeliefhebbers zich gaan afvragen of hun koopje wel zo fris is.”

Christa: „De organisatie van het Bangladesh Veiligheidsakkoord heeft de eerste controles gedaan. In eerste instantie tien fabrieken en 250 in de afgelopen maand. Voor eind september moeten alle 1600 fabrieken die onder het akkoord vallen, op brand- en bouwveiligheid worden doorgeleefd. Er

zijn tot dus ver nog niet net zulke grote gevaren gevonden als bij het Rana Plaza gebouw, maar geen enkele fabriek slaagde voor de controle. De fouten die werden gevonden - slechte bedrading, te zwaar belaste vloeren - moeten daarna direct worden opgelost. Als er structurele problemen worden gevonden, is het kledingmerk dat in de fabriek kleding laat maken medeverantwoordelijk om de boel op te knappen.”

Wat moet er nog gebeuren?

Natascha: „Mensen zijn gefocust op maar één ding: of het materiaal, of het product, of het proces. Terwijl er gekken moet worden naar het geheel. We moeten de impact van alles, van het maken tot het einde van het product, in kaart brengen, cijfertechnisch. Pas dan kun je gaan vergelijken. Het lastige is dat veel data en gegevens niet beschikbaar zijn, of niet volledig. Er is veel geheimhouding in de productie-wereld. Er moet meer openheid komen. En ontwerpers moeten beter op de hoogte zijn van dat hele proces. Die zijn de bron van nieuwe ideeën.”

Christa: „Eind vorig jaar heeft de Schone Kleren Campagne in samenwerking met de Internationale Arbeidsorganisatie, kledingmerken en vakbonden een fonds opgericht om de (families van) de slachtoffers te compenseren voor zowel medische kosten als verlies van inkomsten. Veel families zitten al bijna een jaar zonder geld. In totaal is er 20 miljoen euro nodig om alle slachtoffers de komende jaren te kunnen helpen. En dit is hard nodig. Alle merken die in Rana Plaza kleding lieten maken, moeten meebetalen. Primark, C&A en Inditex (Zara) hebben een eerste bijdrage gedaan, maar Benetton weigert de mensen die haar kleding maakten, te compenseren. Het enige merk dat aanzienlijk heeft bijge-

dragen is Primark.”

Komt het ooit goed?

Lynsey: „Er is zeker reden tot hoop. Maar de aanhoudende populariteit van fast fashion in onze winkelstraten is geen goed nieuws voor eerlijke werk-omstandigheden in de textielindustrie. Want dat systeem van snel wisselende, goedkope collecties is lastig verenigbaar met principes zoals redelijke werkwijzen, betrouwbare arbeidsomstandigheden en eerlijke lonen voor werknemers van kledingfabrieken.”

Natascha: „Ik wil uiteindelijk komen tot kleding waar iedereen blij van wordt, zowel de makers als de dragers. Want uiteindelijk moet iedereen blij zijn. Mensen zullen zich altijd willen blijven sieren en kleding zal altijd belangrijk blijven. Dus er zal altijd gezorgd worden, en moeten worden, dat het beter wordt. Er is nog een lange weg te gaan; ik heb nog tot mijn pensioen werk.”

Doe-het-zelf

Vandaag op Fashion Revolution Day opent het Humanity House in aanwezigheid van minister Ploumen voor Buitenlandse Handel en Ontwikkelingssamenwerking de nieuwe tentoonstelling Fair Fashion Lab in Den Haag. Hier wordt door onder andere ontwerper Monique van Heist, trendwatcher Hilde Roehart en onderzoeker Natascha van der Velden gezocht naar creatieve oplossingen voor de problemen in de kledingindustrie. Ook bezoekers worden uitgedaagd na te denken over antwoorden op dit probleem. De expositie loopt tot en met 31 december 2014.



Foto uit 2010 van een kledingfabriek in Bangladesh. Er is inmiddels het nodige verbeterd, maar er is nog genoeg werk aan de winkel. FOTO: AFP

Fig. A5b Article in Sp!ts (267,000 copies), Thursday 24th April 2014, p.3

Fair Fashion Lab in Humanity House

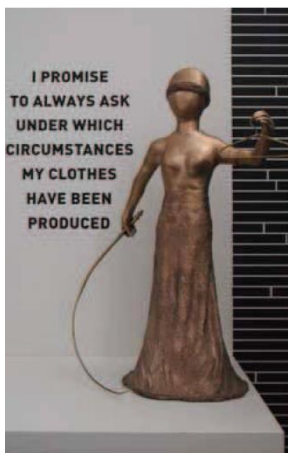
Zes ideeën over eerlijke mode



De witte T-shirts gaan na afloop van de tentoonstelling terug naar het inzamelcentrum van KICI. ► Foto's: DHC



Er kan naar hartenlust geknipt worden in de oude lappen om een nieuw tapijt te maken.



Achter de zwarte stickers in de opstelling van Arne Hendriks schuilen de namen van alle slachtoffers van de ramp in Rana Plaza.

Wat weet je van de kleren die je dagelijks draagt? Waar komen ze vandaan? Wie heeft ze gemaakt? Eenvoudige vragen waarop menig een het antwoord schuldig moet blijven. De tentoonstelling Fair Fashion Lab in het museum Humanity House biedt ook geen uitkomst, maar laat wel zien hoe het beter kan.

Door Jasper Gramsma

De instorting van de Bengaalse textielfabriek Rana Plaza, deze week op de kop af een jaar geleden, is voor Humanity House aanleiding om de menselijke kant van de oneerlijke kledingindustrie te belichten. Met meer dan duizend doden was de ramp één van de grootste, maar zeker niet de eerste in zijn soort. Frederiek Biemans, verantwoordelijk voor de expositie Fashion Lab: "Het probleem is veel groter dan die ene fabriek. Zelfs als je designerkleding koopt waar 'Made in Italy' in staat, kan het zijn dat alleen de knopen er in Italië zijn aangezet terwijl de rest alsnog uit Bangladesh of Cambodja afkomstig is. Transparantie ontbreekt en daarom willen wij het met deze tentoonstelling gemakkelijker maken voor consumenten om te bedenken wat zij zelf kunnen doen. Wij geven daarvoor handvatten". Biemans merkt daarbij op dat het hier niet per se over duurzaamheid gaat: "Dat heeft op langere termijn natuurlijk ook impact, maar het gaat ons om de humanitaire kant". Fashion Fair Lab benadert het thema eerlijke mode vanuit verschillende disciplines. "Uiteraard is er een kledingontwerper op de tentoonstelling vertegenwoordigd: Monique van Heist. Ontwerpers zijn immers belangrijke spelers in de branche. Ook wilden we graag kunstenaars Arne Hendriks en Tinkebell erbij, omdat zij breder durven te denken en met onvoorspelbare suggesties komen die prikkelen. Hilde Roothart, de trendwatcher op deze tentoonstelling, kan ons vertellen van welke ontwikkeling we onderdeel zijn zonder dat we het zelf weten. En tot slot geeft Natascha van der Velden van de TU Delft een kijkje in de toekomst. Als wetenschapper is zij met zaken bezig waar de consument nog geen weet van heeft", legt Biemans uit. Allemaal kregen ze dezelfde opdracht mee: laat zien hoe de toekomst van de mode eruit ziet met humaniteit in het achterhoofd.

Gordijnen

Het resultaat is even uiteenlopend als de deelnemers zelf. Gordijnen, gemaakt van 656 witte en bijna witte tweedehands T-shirts vormen het decor, ontworpen door de architecten van Space & Matter. Bij binnenkomst ontstaat een melange van wasmiddelen uit het decor. Biemans: "Iedereen heeft wel zo'n wit shirt in de kast, maar niemand weet eigenlijk waar het vandaan komt. Daarmee wordt direct al de eerste vraag opgeroepen". In de gordijnen zitten openingen naar vijf kamertjes. Het eerste kamertje dat Biemans binnenstapt, is van trendwatcher Hilde Roothart. Er hangt een groot gaas aan de wand dat de bezoekers de komende maanden met stroken afgedankte kleding verweven tot een tapijt. "Roothart ontwaart de trend dat consumenten na decennia van verwijdering weer steeds meer betrokken zijn bij de makers van hun producten. Door gezamenlijk aan het tapijt te werken, dat eind dit jaar bij 3FM's Serious Request zal worden geveild, probeert Roothart de relatie tussen maker en gebruiker te herstellen", vertelt Biemans. Het project genaamd Maker Movement is geïnspireerd op het Marokkaanse initiatief 'Carpet of Life'.

Mensenbotten

Schuin tegenover het kamertje van Roothart staat een gedenkplek van kunstenaar Arne Hendriks. Hij doet een eenvoudige oproep aan de bezoeker: "Belooft dat je altijd zult vragen onder welke omstandigheden mijn kleren zijn gemaakt". Biemans: "Die belofte doe je in een envelop die degene na jou meeneemt om je eraan te houden. Zelf mag je een sticker van de achterwand halen waaronder de naam van één van de slachtoffers van Rana Plaza tevoorschijn komt". Hendriks hoopt dat steeds meer mensen naar de herkomst van hun kleding gaan vragen, waardoor bedrijven verplicht zijn een antwoord te geven en zich bewust worden van hun eigen gedrag. De installatie van kunstenaar Tinkebell, ernaast, is de komende weken nog in aanbouw. Voor het project 'Save the World' reisde zij af naar Bangladesh om verslag te doen van de kledingindustrie. Steeds stuurt ze een kaart naar



De 'bodyfur dress' van Natascha van der Velden. ► Foto: James Brown en Gregory Dean

het museum als dagboekfragment die aan een grote kalender wordt toegevoegd. "Ze heeft al geprobeerd een memorial op te richten voor de slachtoffers van Rana Plaza, maar dat is door de overheid geweigerd. Dit is een spannend onderdeel van de tentoonstelling, omdat we het eindresultaat niet kennen. Zeker met Tinkebell is dat een verrassing". De controversiële kunstenaar heeft dezer dagen mensenbotten gekregen van nabestaanden die rondlopen op de rampplek Rana Plaza. Ze kijkt hoe ze daarvoor een waardige bestemming kan vinden.

Tijdelijkheid

Met haar project 'Hello Fashion' wil kledingontwerperster Monique van Heist een statement maken tegen de tijdelijkheid van mode. Ze vindt dat kleding gedragen moet worden tot het versleten is. Daarom kunnen bezoekers met van Fair Fashion Lab meegenomen patronen thuis hun eigen jassen maken met een protesttekst. "Deze protestcoats zijn geïnspireerd op de jaren tachtig, toen punkers zich individueel uitdrukten. Het zou leuk zijn als de bezoekers zelf laten zien wat ze ervan hebben gemaakt door een foto opte sturen", aldus Biemans. Natascha van der Velden van de TU Delft werpt een blik in de toekomst die voor de meesten ongrijpbaar is. De promovende onderzoeker hoe je als consument op alle fronten verantwoord kunt handelen bij de aankoop van bijvoorbeeld kleding, voeding en telefoons. Daarvoor ontwikkelt zij het EcoDesign Strategy Wheel dat bestaat uit acht elementen waaraan te zien is of een product voldoet. De combinatie van onder meer materiaal, transport, productie en levensduur geeft elk artikel zijn eigen vingerafdruk. Van der Velden geeft ook voorbeelden van producten die hoog scoren: een 3D-printer en olifantengras, dat dichtbij huis groeit en ge-

schikt is om te verwerken tot textiel. Als ultieme oplossing stelt ze een speciale pil voor die haargroei op bepaalde plekken van het lichaam bevordert, zodat er kleding van gemaakt kan worden. "In dat geval ben je tegelijkertijd maker, ontwerper en consument. Daarmee schaad je niemand", aldus Biemans.

Waardeloos

Voor de tentoonstelling werkte Humanity House samen met de Schone Kleren Campagne, die al jaren strijdt voor bewustwording van de consument. "Een van de campagnes vertelde me dat er een keerpunt is ontstaan in het denken over fast fashion. Toch zijn de jongeren in het voortgezet onderwijs gewend dat ze elk seizoen nieuwe kleren kunnen kopen, waardoor kleding waardeloos lijkt. Voor ons is dat een hele belangrijke doelgroep die we met het educatieprogramma willen bereiken". Film is ook onderdeel van het concept. Zo zal in juni de documentaire 'China Blue' te zien zijn, over de meisjes die werken in de Chinese spijkerbroekenindustrie.

Hoewel de grote marktpartijen op de expositie buiten beschouwing zijn gelaten, gaat Humanity House wel met ze in gesprek. "We hebben ze uitgenodigd om zich te laten inspireren en zich bewust te worden van hun positie in de keten", vertelt Biemans. "Onder meer G-Star en de branchevereniging VGR zijn bij de opening aanwezig. Daarnaast willen we met debatten en een festival in het najaar de dialoog tussen de bedrijven en de consument aanzwengelen, zodat men weet waar men op moet letten".

Fair Fashion Lab, Humanity House, Prinsegracht 8, 24 april tot en met 31 december, 20.00 uur, prijzen vanaf € 5,00. Meer informatie: www.humanityhouse.org.

Fig. A6 Article in Den Haag Centraal (9,000 copies, reaches 20,700 persons), Friday 25th April 2014, p.16

Annex II

A.2 The sustainable development design method (SDDM)

Although *sustainable development* can also be regarded as a philosophy, a concept or a theory, it can, through the eyes of the author of this thesis, also be considered as (part of) a procedure⁹⁸ towards sustainability. This procedure (= the method) itself is not defined (yet), but the fulfilment of the Sustainable Development Goals (SDGs; UN, 2015, see Figure B1) should be the outcome (author's quotation).



Fig. B1 The Sustainable Development Goals (SDGs; UN, 2015)

In September 2015, the United Nations Member States adopted the SDGs as part of "... a new sustainable development agenda, that will build on the Millennium Development Goals" (UN, 2015). These goals include environmental goals as well as social sustainability aspects and the triple bottom line People, Planet and Prosperity (see Figure B2).

From the viewpoint of the author of this thesis, behind these goals, lie many (and maybe all) possible (design) opportunities towards sustainability on a global scale. In the coming years, next to the

⁹⁸ In Dutch: *werkwijze* for which Van Dale Grote woordenboeken versie 5.0 gives the following translation:
 (van machine) mode of operation, operating procedure
 (van personen/commissies) **method** (of working), procedure
 (bij fabricage) (manufacturing) process
 (routine) routine (vaak informeel)

implementation of the 2030 Agenda for Sustainable Development⁹⁹, all countries and all stakeholders acting in collaborative partnership must unravel the 17 goals and translate these into specific actions that the actors involved can undertake to accelerate sustainable development. The procedure to arrive at the SDGs could, for example, be named the *sustainable development method* (author's quotation), and the actions of designers could be grouped under the header: *the sustainable development design method*. (SDDM; *ibid.*)

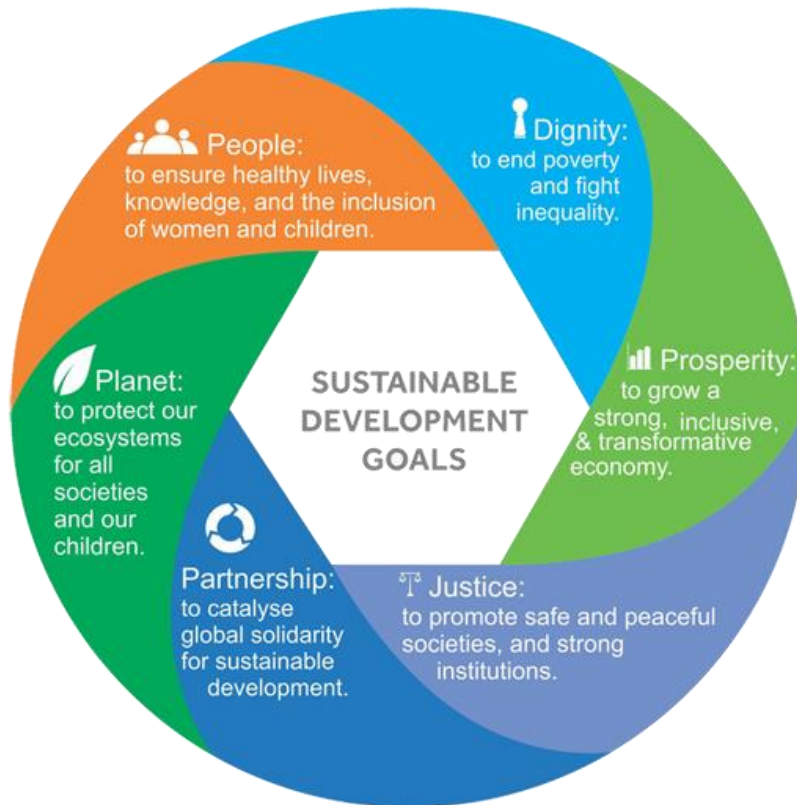


Fig. B2 The SDGs are based on and built around the triple bottom line (UN, 2015)

In addition to the goal of this research (as described in Section 2.1), for this thesis, the covering aim, in retrospect, is to contribute to sustainable development in the line of thought of the developers of the SDGs. From this perspective, and referring to the target group of this research, it would be interesting – but also a lot of work and out of the scope of this research – to explore* how much *designers* can actually contribute to these goals. Currently, doctoral student Rebecca Ruebens of Delft University of Technology and Rhizome is exploring this question and has been developing the 'Holistic Sustainability Checklist' and 'Label' to assess and "...illustrate the holistic parameters relevant at each stage of a product's generic production to consumption system..." (Ruebens, 2016)

⁹⁹<https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf>

*For example, it can be argued that designers are able to contribute to SDG 1 'no poverty' by means of developing design concepts that create (more) jobs (than the current situation, e.g. by proposing an option to hand in the product for repair). The question of whether or not this notion is sustainably sound came to the fore during the ID4175 Advanced Embodiment Design Sustainable Design Engineering course for masters' students, at the Faculty of Industrial Design Engineering this year (2016). The design students were pointing out that more jobs cost more money, so company management might not appreciate this sustainable solution. This is true (of course), unless the students can figure out a way to earn more money with the newly developed product or service system concept (or find other ways to satisfy the company management, e.g. convince the board that the extra costs will pay off in customer loyalty, etc.).

Alternatively, designers might be in a less advantageous position to contribute to, for example, SDG 16 'peace and justice and strong institutions', because this is beyond the reach of their influence. But it could as well be, since designers are generally known for their creativity, that case studies and design interventions will prove differently and that designers *are* capable of finding solutions to fulfil this (and the other) goal(s).

It is the author's suggestion that, by this means, all SDGs could be analysed to obtain an overview and to finally construct the *sustainable development design method*.

Biography

Natascha M. van der Velden (1969) is an industrial design engineer, educated at the Delft University of Technology. Before the turn of the millenium, Van der Velden worked as a product manager in the fashion industry and the graphical industry. In this position, she gained experience in managing complex, commercial, product development and manufacturing processes, which has been valuable for her further career as an independent entrepreneur but also for her latest career move towards the title of Doctor of Philosophy.

When Rotterdam became the European Capital of Culture in 2001, Van der Velden left the industrial sector and entered into the cultural sector as an independent design consultant, initiating and managing artistic, literary and design projects. During these activities, she also carried out product development projects with several reputable design agencies. All her work has always been in close connection and cooperation with (combinations from) the creative, design and fashion disciplines.

Since 2010, Van der Velden has been an author of several publications on fashion and sustainability; among others, a course book for fashion entrepreneurs, project reports and scientific papers. She has presented her scientific work at symposia and other events and given lessons and workshops about this subject at companies, universities and other educations.

In March 2014, Natascha van der Velden was asked by Marion Vredeling of TU Delft Library to present herself as a Living Book, for PhD colleagues and also Rector Magnificus Karel Luyben. For the book cover of her Living Book she chose a bird's feather, or more specifically, the feather of a peacock. Birds wear feathers for protection, to impress or for camouflage and to fly wherever they want to go, to pick up food (for thought) to grow. The latter reflects Van der Velden's way of life. And besides, the peacock is one of the most fashionable birds on earth. And just for your information: Peacocks *can* fly, but within the bounds of possibility.

Since July 2016, Van der Velden has been working on a circular textile project, under the Climate-KIC Partner Accelerator Programme, supported by the EIT, a body of the European Union, together with TU Delft and the company DutchSpirit. Simultaneously, she explores the possibilities for cooperation on projects about the sustainability of textiles, with several affiliates from the network she established during her PhD.

Alongside her project based work, Van der Velden also intends to broaden her teaching activities on ecodesign and LCSA of textiles, products and service systems, and has many ideas about new research and possible publications.

Her ambition is to support and accelerate the information transfer about the sustainability of textiles between the scientific community, designers, consumers, governments and business practice.

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Part II: Publications

The mind map is a complex, hand-drawn diagram titled "TU Delft Humanity House" and "Part II: Publications". It is centered around a circular diagram with "CRADLE 2 CRADLE" at the top and "USE" at the bottom. The central circle is surrounded by a ring of text: "CAUSING", "WASTE", "TRANSFER", "PRODUCTION", "WASTE", "USE", "END-OF-LIFE", "MATERIAL".

The map branches out into various sections:

- 3D**: Includes a 3D model of a person and notes about "3D printing" and "3D scanning".
- FASHION**: Includes a drawing of a dress and notes about "fashion" and "design".
- MAP**: Includes a map of the Netherlands and notes about "map" and "design".
- INDELING**: Includes a diagram of a house and notes about "indeling" and "design".
- Tag**: Includes a drawing of a tag and notes about "tag" and "design".
- Design Goal**: Includes a goal statement: "By making better use of how & existing knowledge we want to create an optimal & scalable production of our design. This will lead to an improved place quality and of the city's health." and notes about "design" and "goal".
- WUR**: Includes a drawing of a person and notes about "wur" and "design".
- AM**: Includes a drawing of a person and notes about "am" and "design".
- PLASTIK**: Includes a drawing of a plastic bottle and notes about "plastic" and "design".
- FAIR FASHION**: Includes a drawing of a person and notes about "fair fashion" and "design".
- WURZEL**: Includes a drawing of a root and notes about "wurzel" and "design".
- MODE**: Includes a drawing of a person and notes about "mode" and "design".
- CRADLE 2 CRADLE**: Includes a drawing of a person and notes about "cradle 2 cradle" and "design".
- USE**: Includes a drawing of a person and notes about "use" and "design".
- END-OF-LIFE**: Includes a drawing of a person and notes about "end-of-life" and "design".
- MATERIAL**: Includes a drawing of a person and notes about "material" and "design".

The map also includes various notes, diagrams, and references to "TU Delft" and "Humanity House".

Publication 1: LCA benchmarking study on textiles P.1

Van der Velden, N. M., Patel, M. K., & Vogtländer, J. G. (2014). LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane. *The International Journal of Life Cycle Assessment*, 19(2), 331-356

LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane

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Joost G. Vogtländer

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Abstract

Purpose The purpose of this paper is to provide an improved (up-to-date) insight into the environmental burden of textiles made of the base materials cotton, polyester (PET), nylon, acryl, and elastane. The research question is: Which base material and which life cycle stage (cradle-to-gate as well as cradle-to-grave) have the biggest impact on the environment? **Methods** Life cycle inventory (LCI) data are collected from the literature, life cycle assessment (LCA) databases, and emission registration database of the Dutch government, as well as communications with both manufacturing companies of production equipment and textile companies. The output of the calculations is presented in four single indicators: Eco-costs 2012 (a prevention-based indicator), CO₂ equivalent (carbon footprint), cumulative energy demand (CED), and ReCiPe (a damage-based indicator).

Results and discussion From an analysis of the data, it becomes clear that the environmental burden is not only a function of the base materials (cotton, PET, nylon, acryl, and elastane) but also of the thickness of the yarn (for this research, the range of 50–500 dtex is examined). The authors propose that the environmental burden of spinning, weaving, and knitting is a function of 1/yarn size. The cradle-to-grave analysis from raw material extraction to discarded textile demonstrates that textiles made out of acryl and PET have the least impact on the environment, followed by elastane,

nylon, and cotton. The use phase has less relative impact than it is suggested in the classical literature.

Conclusions The impact of spinning and weaving is relatively high (for yarn thicknesses of less than 100 dtex), and from the environmental point of view, knitting is better than weaving. LCA on textiles can only be accurate when the yarn thickness is specified. In case the functional unit also indicates the fabric per square meter, the density must be known. LCA results of textile products over the whole value chain are case dependent, especially when dyeing and finishing processes and the use phase and end-of-life are included in the analysis. Further LCI data studies on textiles and garments are urgently needed to lower the uncertainties in contemporary LCA of textile materials and products.

Keywords Carbon dioxide (CO₂) · Clothing · Eco-costs · Fibers · Spinning · Textile · Use phase · Weaving

1 Introduction

In recent years, life cycle assessment (LCA) has been increasingly adopted by textile and apparel companies. Many actors in the textile and clothing chain such as fiber manufacturers (e.g., Lenzing, Advansa, Dupont), producers of flooring material (e.g., InterfaceFlor, Desso, Heugaveld), fashion brands (united in the Sustainable Apparel Coalition), and even umbrella organizations (European Commission and the Dutch branch organization Modint) use LCA to assess the environmental impacts of textile-related products. In addition, educational textile and fashion institutes (e.g., the Amsterdam Fashion Institute) have moved towards life cycle thinking, picking up the signals from companies and other organizations.

In many cases, LCA studies and the development of LCA tools on textile products are carried out by consultancy companies or independent research institutes which interpret

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LCA and the International Standard Organization (ISO) specifications in their own way. Results are presented in reports or online and reach the public via marketing departments or via the media. Despite of this growth in LCA work, not many (recent) LCA studies on textile products can be found in scientific literature. Consequently, there are gaps in the scientific framework for the interpretation of the previously mentioned market efforts. There is not enough literature available and there are no (open source) life cycle inventory (LCI) databases to build further scientific research upon. Nondisclosure of databases and company-related information might be due to the fact that confidentiality plays an important role. This article aims to open up the scientific discussion on LCA in textiles.

1.1 Existing LCA studies on textiles

A literature survey and some investigations among experts in the field of LCA studies on textiles showed that most of the publicly available LCA data and process data are outdated, not transparent (especially regarding system boundaries), and sometimes clearly out of range (outliers). It was quickly concluded that original data reflecting today's situation is urgently needed.

A summary of the results of the literature survey is given in the succeeding paragraphs and sections. Collins and Aumônier (2002) compiled the LCI data upon references dating from 1978 to 1999. Another research executed by Kalliala and Talvenmaa (1999) reports, for example, spinning energy which is derived from a study out of 1997. In-depth investigation on weaving led to the research of Koç and Çiñçik (2010), but an analysis of the references revealed that only 5 out of 16 references were in English, which makes it very difficult to verify the results. In the recent thesis of Shen (2011), nonrenewable energy use for the production processes of different fabrics is given, based upon a report from 1997 (Laursen et al. 1997). Another recently published LCA study of Walser et al. (2011) uses inventory data for polyester (PET) textile production, partly built upon information dating from 1997 as well. The authors also noticed that the data in the Ecoinvent database (Ecoinvent 2010) on cotton and bast fibers do not specify the yarn size, which has an important influence on energy use. This aspect is further discussed in Section 3.

In general, it appeared to be very difficult to check the underlying datasets because researchers built up their own dataset by combining information from different and sometimes very old or confidential sources.

Tobler-Rohr (2011) gives an excellent overview of textile production but does not provide enough LCI data to base further LCA calculations on.

Steinberger et al. (2009) present a comprehensive LCA study on clothing which is focused on the use phase of textiles

(i.e., washing clothes by the user); however, this lacks accurate data on the production phase.

1.2 Data collection

Most of the previously mentioned sources were considered to be not very valuable for our LCA on textiles conducted in 2011–2012 because, in the preceding period, companies may have made significant improvements on energy consumption, mainly driven by high energy costs. Firm underpinning numerical data for this change was not transparent, but percentages of 2 to 3 per year are quoted. A report of the united German textile machinery manufacturers (VDMA 2009) claims energy efficiency improvements of 15 % over the last 10 years. This figure was also quoted during a communication with Mr. Bernard Defraye of CIRFS, the European Man-Made Fibres Association.

An important observation is that the majority of the researchers do not take into account important technical specifications (e.g., the thickness of the yarn) which have a major impact on processing energy, as will be shown in Section 3.

The approach chosen in this study was, therefore, to collect all available data from the public domain (scientific literature and company information), from (LCA) databases, from the emission registration database of the Dutch government, and by contacting companies and experts.

We contacted (among others) the following companies/associations:

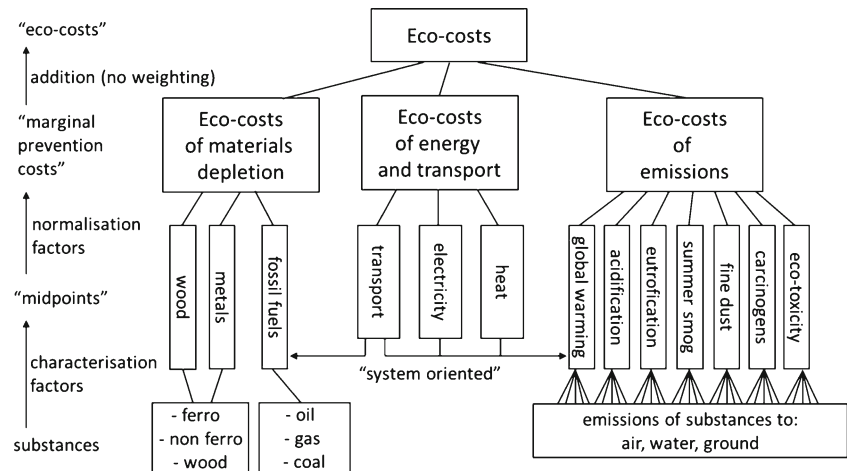
- Oerlikon Barmag,
- CIRFS, the European Man-Made Fibres Association,
- International Textile Manufacturers Federation (ITMF),
- Kuempers.

2 Goal and scope

2.1 Goal

The goal of the study is to develop an improved (up-to-date) insight into the environmental burden of the life cycle of textiles, for various types of materials (cotton, PET, nylon, acryl, and elastane), and as a function of the thickness of the yarn in the range of 50–500 dtex (decitex=the mass in grams per 10,000 m). The main focus is on the production of textiles (cradle-to-gate); some data on the use phase (washing by the user) and the end-of-life phase are also provided.

Since the goal of the study is to provide designers with environmental information, the output of the calculations is not presented in the form of a set of midpoints, but in the form of single indicators. A single indicator in LCI analysis is one single score to express the result of the cumulative inventory list in one indicator, either at the midpoint or endpoint level.

Fig. 1 Calculation structure of the Eco-costs 2012

To provide the reader with information on the effect of the choice of a single indicator, data on four single indicators are given:

- Eco-costs 2012 (a prevention-based indicator),
- CO₂ equivalent (a single indicator at midpoint level),
- Cumulative energy demand (CED),
- ReCiPe (a damage-based indicator).

Eco-costs is a measure to express the amount of environmental burden of a product on the basis of prevention of that burden and has also been introduced in this journal before (Vogtländer and Bijma 2000, 2001). They are the costs which should be made to reduce the environmental pollution and materials depletion in our world to a level which is in line with the carrying capacity of our earth. The eco-costs system has been updated in 2007 and in 2012. The characterization (“midpoint”) tables which are applied in the Eco-costs 2012 system are (see Fig. 1 and Vogtländer 2013):

- IPPC 2007, 100 years, for greenhouse gasses;
- USETOX, for carcinogens and ecotoxicity;
- ReCiPe, for acidification, eutrophication, and summer smog (photochemical oxidant formation);
- IMPACT 2002+, for fine dust.

Eco-costs is part of the bigger model of the eco-costs value ratio (EVR) and the method of eco-efficient value creation (Wever and Vogtlander 2012; Mestre and Vogtlander 2013).

The advantage of the single-issue indicators (CO₂ equivalent and CED) is that they are simple to understand. The disadvantage, however, is that toxicity and materials depletion is not taken into account. That is the reason why data on eco-costs and ReCiPe are given as well: they both incorporate human toxicity, ecotoxicity, materials depletion, and land use.

ReCiPe is a damage-based indicator. It is the successor of the famous Eco-indicator 99, introduced in this journal (Goedkoop et al. 1998). We present the data for the Europe H/A weighting set for human toxicity, ecotoxicity, and materials depletion (H/A refers to the default ReCiPe endpoint method, H=hierarchist and A=average weighting set).

2.2 Scope, system boundaries, and declared unit

The scope of this study is cradle-to-grave. It includes the cradle-to-gate processes of the production chain from raw material extraction to manufactured greige¹ fabric for cotton, PET, nylon, acryl, and elastane, as well as the gate-to-grave processes for textile products made out of these materials.

The LCAs for greige textile manufacturing phases are full analyses. For dyeing and finishing processes, ranges and an example of LCA based on best practices are given. A cutoff criterion of 1 % is applied to decide on the exclusion of (sub)processes, inputs, and outputs, in compliance with ISO 14044 Section 4.2.3.3. For the use phase and the end-of-life phase, ranges are given based on specific cases. The scope excludes the following phases related to the textile product: manufacturing (sewing and assembling), distribution, marketing, and sales of the textile.

The choice of the declared unit (functional unit) is “1 kg of (greige) textile.” This paper shows that a unit in kilograms is a logical choice from the point of view of production, since the eco-burden of the base materials, spinning, and weaving of all materials is a function of kilograms and yarn size (decitex). However, from the point of view of textile applications (cloth, carpets, etc.), it seems logical to have a declared unit in 1 m², so Section 8 provides some information per square meter.

Table 1 summarizes the scope of this study and simultaneously explains the outline of this article. The full cradle-to-gate analyses on the production of materials in phase A and phase 1 are based on Ecoinvent LCIs (Ecoinvent 2007a, b). These LCIs include transport and the required production infrastructure (the so-called third-order LCIs).

¹ The term “greige” is industry jargon for “untreated woven or knitted fabric” and refers to the fabric before the final phases of dyeing and finishing. In this context, “greige” is defined as “unbleached and undyed or untreated.”

To determine whether the impact of the emissions from the following production process steps stays below the 1 % cutoff criterion, the emission registration database of the Dutch government (<http://www.emissieregistratie.nl/erpublic/bumper.nl.aspx>, accessed on 20 January 2013) is used. This database shows that emissions from the production sites of process phases B to D and 2 to 5 are less than 1 % of the emissions from the production of electricity and heat, so these emissions are below the 1 % cutoff criterion and are not taken into account.

The results of the analyses of the previously mentioned processes for greige fabric are included in Sections 4.1 and 4.2.

The Dutch emission database shows that emissions from production facilities for dyeing and finishing are above the 1 % cutoff criterion, so these emissions coming from phases E, F, 6, and 7 are included in the analyses. Note that the emissions of these process phases are highly dependent on the fact whether or not modern best practices of green production are used and on the specific colors and finishing processes. Only data on best practices in the Netherlands have been analyzed, since data from production facilities in other areas (for instance, India and China where the situation is without doubt expected to be much worse) are not available. Results of the analyses of the gate-to-gate processes E, F, 6, and 7 are included in Section 5.2.

The use phase (G and 8) and the end-of-life phase (H and 9) are strongly case dependent. For these phases, a few scenarios are provided in Section 6 to show the reader how important these phases are compared to the production phases.

In conclusion, Section 7 gives an overview of the breakdown of the environmental burden over the complete textile life cycle. Transportation in the first step of material production (polymers and cotton) is included; however, we disregarded transportation in the subsequent production chain for the following reasons:

- The extent of transportation services is very case specific and it, therefore, does not seem possible to develop generic estimates; moreover, a fair part of the environmental impacts caused by transportation cancels out across the options studied (the principle of “streamlined LCA”; Todd and Curran 1999).
- The pollution caused by the transportation of fabric is generally small compared to the pollution of other processes in the production chain, in particular material production. (Shipping textile products from China causes the following extra scores per kilogram: eco-costs, €0.078; carbon footprint, 0.16 kg CO₂ equivalent; CED, 2.6 MJ; ReCiPe, 0.02 Pt).

For electricity from the grid, the data of the UCTE (average electricity production in the European Union [EU]) has been applied. The reason for this choice is that the situation is quite dependent on the specific area. For instance, there are areas in China with old power plants which are extremely polluting, but more and more areas with modern power plants with pollution standards similar to the standards in Europe arise (Ecoinvent 2007c).

Table 1 Scope of research and outline of article

Process/life cycle phase		Specifications of analysis	Discussed in	Results in	
Cotton	Synthetics (polyester, nylon, acryl, and elastane)				
(A) Fiber production (cultivation and cotton treatment)	1. Polymer production (covering all process steps from the extraction of resources)	LCA based on Ecoinvent data	Section 3.2	Section 4.1 for processes (A) to (D) for greige cotton textile	Figs. 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12 for processes (A) to (D) and 1 to 5
(B) Spinning to yarn	2. Spinning of filament	LCA as function of yarn thickness	Section 3.3	Section 4.2 for processes 1 to 5 for greige cotton textile	
(C) Weaving or knitting	3. Texturing 4. Weaving or knitting		Section 3.4 Sections 3.5 and 3.6		
(D) Pretreatment	5. Heat setting of fabric including washing	LCA based on energy	Section 3.7		
(E) Dyeing of fabric	6. Dyeing of fabric	Ranges and example of LCA based on best practice given	Section 5.1	Section 5.2	Processes (E) to (H) and 6 to 9 are case dependent
(F) Final finishing including drying	7. Final finishing including drying		Section 5.1	Section 5.2	
(G) Use phase	8. Use phase	Data given	Section 6.1	Section 6.1	
(H) End-of-life	9. End-of-life	Data given	Section 6.2	Section 6.2	

An overview over the complete life cycle is discussed in Section 7 and depicted in Figs. 13 and 14

Table 2 Cotton fiber production and spinning: data from literature and private communication

Process step/source	Quantity	Specification of process and/or extra remarks	Specification of product (CO=cotton)	Yarn count (den)	Yarn count (dtex)	Electricity (kWh)	Steam (MJ)	Natural gas (MJ)	Liquefied petroleum gas (MJ)	Diesel (MJ)	Light fuel oil (MJ)	Heavy fuel oil (MJ)	Hard coal (MJ)	Water (L)
Fiber manufacturing														
Cotton fiber production	Fiber													
IFTH2 (n.a.)	1 kg	Intensive production (6 countries)	Cotton fiber			0.41		0.00	0.50	8.21				7,103.00
IFTH2 (n.a.)	1 kg	Biological production (6 countries)	Cotton fiber			0.41		0.00	0.50	8.21				7,103.00
Laursen et al. (2007) EDIPTEX	1 kg	Cotton cultivation and harvesting				0.91		6.33	0.58	8.21	4.13			2,000.00
Laursen et al. (2007) EDIPTEX	1 kg	Fiber production of cotton yarn according to figure 1.3	Cotton fiber including cultivation and harvest			13.89								
Yarn manufacturing														
Spinning	Yarn													
ITMF (2008)	1 kg	Rieter ring spinning (including winding)	CO combed ring, yarn 1 1/8 in., 30 Ne	180	200	3.34								
ITMF (2008)	1 kg	Rieter rotor spinning	CO carded, rotor yarn=open end 1 1/16 in., 20 Ne	265	300	1.42								
ITMF (2010)	1 kg	Rieter ring spinning (including winding)	CO combed ring, yarn 1 1/8 in., 30 Ne	180	200	3.42								
ITMF (2010)	1 kg	Rieter rotor spinning	CO carded, rotor yarn=open end 1 1/16 in., 20 Ne	265	300	1.46								
Kaplan and Koç (2010)	1 kg	Staple fiber to yarn+data are for world average	CO combed ring yarn			3.84								
Kaplan and Koç (2010)	1 kg	Staple fiber to yarn+data are for world average	CO open end yarn			2.54								
Kaplan and Koç (2010)	1 kg	Thermal energy (steam?) is needed for fixation				2.70	1.10							
Kaplan and Koç (2010)	1 kg	Thermal energy (steam?) is needed for fixation				4.00	4.70							
Kaplan and Koç (2010)	1 kg	Only SEC+calculated	CO combed weaving yarn	180	200	3.32								
Kaplan and Koç (2010)	1 kg	Only SEC+reported	CO combed weaving yarn	180	200	3.64								
Kaplan and Koç (2010)	1 kg	Only SEC+calculated	CO combed weaving yarn	108	120	6.81								
Kaplan and Koç (2010)	1 kg	Only SEC+calculated	CO combed knitting yarn	180	200	3.06								
Kaplan and Koç (2010)	1 kg	Only SEC+calculated	CO combed knitting yarn	108	120	5.52								
Confidential source no. 7	1 kg	Rotor spinning of CO				1.85			1.68		1.56			

Table 2 (continued)

Process step/source	Quantity	Specification of process and/or extra remarks	Specification of product (CO=cotton)	Yarn count (den)	Yarn count (dtex)	Electricity (kWh)	Steam (MJ)	Natural gas (MJ)	Liquefied petroleum gas (MJ)	Diesel (MJ)	Light fuel oil (MJ)	Heavy fuel oil (MJ)	Hard coal (MJ)	Water (L)
Dahlöf (2004) Laursen, 1997 lowest limit	1 kg	Total energy demand for cotton spinning factory—6.33 MJ—assumed only electricity				1.76								
Dahlöf (2004) Laursen, 1997 lowest limit	1 kg	Total energy demand for cotton spinning factory—18.31 MJ—assumed only electricity				5.10								
Kaplan and Koç (2010)	1 kg	Ring spinning according to their calculations	CO combed weaving yarn	330	330	1.88								
Kim et al. (1983)	1 kg	Spinning energy usage per unit production (kWh/kg)>no specific material; reported data 1972				5.40								
Kim et al. (1983)	1 kg	Spinning energy usage per unit production (kWh/kg)>no specific material; reported data 1980				4.86								
Collins and Aumônier (2002)	kg product	Spinning including preparation = 29.36 kWh/kg	For pair of cotton briefs (72 g) and pair of polyester trousers (=400 g)			7.46								
Cartwright et al. (2011), Laursen et al. (2007) EDIPTEX	1 kg	Yarn manufacturing	For shirt 65 PET/35 CO staple fibers											
Palamutcu (2010)	1 kg	Carded yarn spinning plant—average actual and estimated				3.30								
Laursen et al. (2007) EDIPTEX	1 kg	Combed ring yarn according to formula	65/35 PET/CO	117	130	4.10								2.20
Laursen et al. (2007) EDIPTEX	1 kg	Combed ring yarn according to formula	100 CO	117	130	4.15								2.20
SimaPro 7.2 educational, Idemat 2012, V0.0	1 kg	Yarn production, cotton fibers/kg/GLO+electricity, low voltage, at grid/CN U				5.10								
SimaPro 7.2 educational, Idemat 2012, V0.0	1 kg	Yarn production, cotton fibers/kg/GLO+electricity, low voltage, at grid/US U				3.40								
Demir and Behery (1997)	1 kg	Ring spun	67 CO/33 PET	167		4.41								
Laursen et al. (2007) EDIPTEX	1 kg	Spinning of cotton yarn according to Fig. 1.3				11.61								2,000.00
Laursen et al. (2007) EDIPTEX	1 kg	Figure 3.3 blending, carding, combing, and spinning of CO and PES staple fibers (0.877 kg)				5.07								
Processor, 2011 phase 1	1 kg	Carding+sliving+spinning+winding	40 PET/60 CO+PES staple fibers	180	200	7.00								

Table 2 (continued)

Process step/source	Quantity	Specification of process and/or extra remarks	Specification of product (CO=cotton)	Yarn count (den)	Yarn count (dtex)	Electricity (kWh)	Steam (MJ)	Natural gas (MJ)	Liquefied petroleum gas (MJ)	Diesel (MJ)	Light fuel oil (MJ)	Heavy fuel oil (MJ)	Hard coal (MJ)	Water (L)
Processor, 2011 phase 1	1 kg	Carding+sliving+spinning + winding	40 PET/60 CO+PES staple fibers	90	100	12.00								
Processor, 2011 phase 2	1 kg	Doubling+twining	40 PET/60 CO+PES staple fibers	180	200	1.60								
Processor, 2011 phase 2	1 kg	Doubling+twining	40 PET/60 CO+PES staple fibers	90	100	3.20								
IFTH1 (n.a.)	1 kg	Ring spinning	CO combed			2.88								
IFTH2 (n.a.)	1 kg					2.32								
														4.76

IFTH1 (n.a.) refers to an unpublished report named: *Extrait de "l'Analyse de Cycle de vie pyjama Bébé"* par l'IFTH. Institut Francais du textile et de l'habillement. IFTH2 (n.a.) refers to an unpublished report named: *Extrait de "aide à la prise en compte de l'environnement dans la conception d'articles textiles"* par l'IFTH. Institut Francais du textile et de l'habillement

n.a. not available

^aThe notation "Kaplan and Koç (2010) Tarakcioglu, 1984" means that Kaplan and Koç (2010) are referring in their publication to another reference (in this case, they refer to a publication of Tarakcioglu out of 1984)

All auxiliaries in phases A and 1 are included, since the Ecoinvent data have been applied here. Auxiliaries for the manufacturing of textile (according to IPPC 2003, among others, dyestuffs, dye carriers, lubricants, detergents, and complexing agents) are not included, since the impact on the calculations is less than the cutoff criterion of 1 % (e.g., the input of dyestuffs based on a high liquor ratio according to the IPPC 2003 "fair practice" causes the following extra scores per kilogram: eco-costs, €0.015; carbon footprint, 0.08 kg CO₂ equivalent; CED, 2.7 MJ; ReCiPe, 0.011 Pt).

3 LCI data—cradle-to-gate for greige textile

3.1 Base materials

The LCI data for cotton fiber and polymer pellets are from Ecoinvent v2.2:

- Cotton, "cotton fibers, ginned, at farm/CN" (CN=China);
- Acryl, "acetonitrile, at plant/RER" (RER=Region Europe);
- Nylon, 50 % "nylon 6, at plant/RER" and 50 % "nylon 66, at plant/RER";
- PET, "polyethylene terephthalate, granulate, amorphous, at plant/RER S";
- Elastane (Spandex, Lycra), "polyurethane, flexible foam, at plant/RER."

3.2 The textile manufacturing process steps in general

All data for the manufacturing process steps of yarn and fabric are obtained by publicly available sources or directly from industry references, as well as information from confidential sources. This data is presented in Tables 2, 3, 4, 5, and 6. From these tables, we selected the LCI data in Section 3 for our calculations in Sections 4 and 5.

Most of the chosen datasets for the calculations come from sources of European origin (except for data on the production of cotton fiber and the data derived from the ITMF 2010).

Important selection criteria for the chosen data were the reliability and traceability of the underlying reference. We rejected LCA data from studies of which the references for the data used for the calculations are not traceable at all or are explained in an unclear manner.

Important references we selected are:

- Report of the ITMF (2010). ITMF is an international association for the world's textile industries based in Zürich, Switzerland. ITMF's (2010) International Production Cost Comparison, which is based on data coming from individual companies, consultants, and textile trade associations, provides—among other cost components—overviews of power costs per kilogram of product and of the cost of

Table 3 Cotton weaving: data from literature and private communications

Process step/source	Quantity	Specification of process and/or extra remarks	Specification of product (CO=cotton)	Yarn count (den)	Yarn count (dtex)	Electricity (kWh)	Steam (MJ)	Natural gas (MJ)	Liquefied petroleum gas (MJ)	Diesel (MJ)	Light fuel oil (MJ)	Heavy fuel oil (MJ)	Hard coal (MJ)	Water (L)
Fabric manufacturing														
Warping and sizing Palamutcu (2010)	Yarn 1 kg	SEC is relatively low compared to steam and heat	Warp yarn			0.01								
Weaving ITMF (2010)	Fabric 1 kg	Mean of 96 Sultex air-jet weaving machines B190 N2 EP11, air conditioning, weaving preparation, cloth inspection, transportation units, warp beam diameter 1,000 mm, cloth beam diameter 600 mm	Fabric of 27.6/27.6 threads/cm, Ne 30 in warp and weft, gray width 168 cm, gray weight 190 g/m	180	200	4.38								
ITMF (2010)	1 kg	Mean of 72 Sultex air-jet weaving machines B190 N2 EP11, air conditioning, weaving preparation, cloth inspection, transportation units, warp beam diameter 1,000 mm, cloth beam diameter 600 mm	Fabric of 24.0/24.0 threads/cm, Ne 20 in warp and weft, gray width 168 cm, gray weight 248 g/m	265	300	2.97								
Confidential source no. 7	1 kg	Weaving with sizing in Sweden + average of three mills producing CO, Trevira, and wool/PA				2.65			1.66		1.53			
Confidential source no. 7, lowest value	1 kg					1.82			1.66		1.53			
Confidential source no. 7, highest value Dahlöf (2004), Laursen	1 kg					4.19			1.66		1.53			
Total energy demand ranges between 10 and 30 MJ—no breakdown reported														
Kalliala and Talvenmaa (1999)	1 kg	Includes singeing and sizing energy (electricity) consumption—5.4 MJ—no breakdown reported												
Kim et al. (1983)	1 kg	Weaving energy usage per unit production (kWh/kg)>no specific material; 1972 reported data				4.76								
Kim et al. (1983)	1 kg	Weaving energy usage per unit production (kWh/kg)>no specific material; 1980 reported data				3.86								
Kim et al. (1983), Van Winkle, 1978	Per shirt	Energy requirements to produce the shirting material for 1 shirt in kWh of fossil fuel equivalents (1 shirt requires 2,368 m ² of fabric and the CO shirt weighs 308 g; CO/PET 270 g and PET 240 g)	Cloth manufacture 100 % CO										18.50	

Table 3 (continued)

Process step/source	Quantity	Specification of process and/or extra remarks	Specification of product (CO=cotton)	Yarn count (den)	Yarn count (dtex)	Electricity (kWh)	Steam (MJ)	Natural gas (MJ)	Liquefied petroleum gas (MJ)	Diesel (MJ)	Light fuel oil (MJ)	Heavy fuel oil (MJ)	Hard coal (MJ)	Water (L)
Kim et al. (1983), Van Winkle, 1978	Per shirt		Cloth manufacture 50/50 PET/CO									20.20		
Kim et al. (1983), Van Winkle, 1978	Per shirt		Cloth manufacture 65/35 PET/CO									20.20		
Kim et al. (1983), Van Winkle, 1978	Per shirt		Cloth manufacture 100 % PET									7.30		
Koç and Çinçik (2010)	1 kg	Warping+sizing+drawing+air-jet weaving—SEC+9.85 kJ/kg for thermal energy (NWE=NWA=30 Ne=180 Td=20 tex)		180	200	5.06								
Koç and Çinçik (2010), Tarakcioglu, 1984 lowest value	1 kg	Electrical energy consumption for 1 kg of woven fabric+8.3–17 kJ/kg for thermal energy=negligible (+sort not specified)				2.10								
Koç and Çinçik (2010), Tarakcioglu, 1984 lowest value	1 kg	Electrical energy consumption for 1 kg of woven fabric+8.3–17 kJ/kg for thermal energy=negligible (+sort not specified)				5.60								
Koç and Çinçik (2010), Visvanathan, 2000	1 kg	2.2–25 kJ/kg for thermal energy=negligible (+sort not specified)				5.75								
Bahr Dahr Textile Share Company (2010)	1 kg	Weaving requires electricity+compressed air+steam				9.44	4.50				9.07			
Collins and Aumônier (2002)	kg product	Weaving including beaming+winding for fabric for a pair of polyester trousers (=400 g) takes 12.60 kWh/kg product				12.60								
Cartwright et al. (2011), Laursen et al. (2007) EDIPTEX	1 kg	Closed-off high-speed air-jet loom	One shirt (65 % PET/35 % CO) weighs 227 g			1.35								
Palamutcu (2010)	1 kg	SEC				1.80								
SimaPro 7.2 educational, Idemat 2012, V0.0	1 kg	Weaving, cotton/GLO U, electricity, low voltage, at grid/CN U				7.08								
SimaPro 7.2 educational, Idemat 2012, V0.0	1 kg	Weaving, cotton/GLO U, electricity, low voltage, production RER				3.03								
Kuempers, 2011, personal communication	1 kg		60 % CO+40 % PES			10.63								
Laursen et al. (2007) EDIPTEX	1 kg	From Fig. 3.3, 6.8 MJ per 1 working jacket of 770 g (fabric 877 g)	Weaving of fabric of 65 % CO+35 % PES			2.15								
Processor, 2011 phase 3	1 kg	6.5 kWh/10,000 picks; 37 picks/cm; 160 cm width	40 PET/60 CO+PES staple fibers	180	200	9.39								

Table 3 (continued)

Process step/source	Quantity	Specification of process and/or extra remarks	Specification of product (CO=cotton)	Yarn count (den)	Yarn count (dtex)	Electricity (kWh)	Steam (MJ)	Natural gas (MJ)	Liquefied petroleum gas (MJ)	Diesel (MJ)	Light fuel oil (MJ)	Heavy fuel oil (MJ)	Hard coal (MJ)	Water (L)
Processor, 2011 phase 3	1 kg	6.5 kWh/10,000 picks; 48 picks/cm; 160 cm width	40 PET/60 CO+PES staple fibers	90	100	19.50								

SEC specific energy consumption, *EPII* a machine name, *Ne* number English (a unit for yarn thickness, 1 Ne= 1/591 tex)

electric power per country. Using this information, it is possible to calculate back the power use.

- An anonymous company (named “Processor, 2011 phase X” in Tables 2, 3, and 4), which is a producer of (among other textile fabrics) shirt material and has production plants in Belgium and France.
- The company Oerlikon Barmag (referred to as “Barmag, 2011” in Table 5), which is a mechanical engineering company offering innovative spinning lines and texturing machines for man-made fibers.
- The EDIPTX study by Laursen et al. (2007), which was set up in close cooperation with more than 15 Danish textile enterprises which contributed with comments on product models and processes or were directly involved in the collection of data and contributed with data on, e.g., chemicals being used, energy consumption, and waste. A lot of (recent) LCA studies, e.g., the Mission Linen report (Cartwright et al. 2011), refer to data contained in this report.

All collected data (and not only the chosen ones) for the gate-to-gate production processes are included in Tables 2, 3, 4, 5, and 6 to inform the reader about all results from the data-collecting activities. The chosen data are justified in the following sections (3.3 to 3.7 and 5.2) and rendered in italics in the Tables 2, 3, 4, 5, and 6.

Note that the textile industry is using several systems to express the thickness of yarn which must not be confused. Two important units are “tex” (mostly expressed in dtex=decitex=0.1 tex) and “denier.” While 1 dtex is equal to 1 g/10 km, 1 den is equal to 1 g/9 km. If a specification of yarn thickness is known, values in both units are presented in the tables.

3.3 Spinning of cotton and polymer filament

For the spinning process of cotton, only electrical power is important for the LCA calculation (the maintenance of the machine can be neglected, as well as the making of it). The results from the data collection are summarized in Table 2.

It was concluded from the physical characteristics of the spinning process that a thinner yarn (lower decitex) is related to a higher energy demand per kilogram, which can be seen in Table 2. Data, without specification of the yarn size, is, therefore, useless (approximately 50 % of the data in Table 2). Data from Ecoinvent is also useless for the same reason.

Figure 2 shows the data of Table 2 with a specified yarn size and which meet the following the criteria:

1. Is most recent.
2. Is for the specific energy consumption (SEC) spinning process of 100 % cotton.
3. The yarn thickness is within scope.

From Fig. 2, it can be concluded that the energy consumption per kilogram yarn is inversely proportional to the yarn thickness in decitex.

Table 4 Cotton knitting, pretreatment, dyeing, and wet processing: data from literature and private communications

Process step/source	Quantity	Specification of process and/or extra remarks	Specification of product (CO=cotton)	Yarn count (den)	Yarn count (dtex)	Electricity (kWh)	Steam (MJ)	Natural gas (MJ)	Liquefied petroleum gas (MJ)	Diesel (MJ)	Light fuel oil (MJ)	Heavy fuel oil (MJ)	Hard coal (MJ)	Water (L)
Fabric manufacturing														
Knitting	Fabric													
ITMF (2008)	1 kg	Mean of 17 Mayer&Cie Relanit 3.2 II circular knitting machines, 30-in. diameter, 24 gg, 96 feeders with side creel	CO ring yarn to a fabric, single jersey Ne 30, unfinished width (open) 192 cm, unfinished weight 230 g/m	180	200	0.19					0.19			
ITMF (2008)	1 kg	Mean of 13 Mayer&Cie Relanit 3.2 II circular knitting machines, 30-in. diameter, 24 gg, 96 feeders with side creel	CO rotor (open end) yarn to a fabric Lapique Ne 20, unfinished width (open) 224 cm, unfinished weight 358 g/m	265	300	0.16					0.19			
ITMF (2010)	1 kg	Mean of 17 Mayer&Cie Relanit 3.2 II circular knitting machines, 30-in. diameter, 24 gg, 96 feeders with side creel	CO ring yarn to a fabric, single jersey Ne 30, unfinished width (open) 192 cm, unfinished weight 230 g/m	180	200	0.19					0.19			
ITMF (2010)	1 kg	Mean of 13 Mayer&Cie Relanit 3.2 II circular knitting machines, 30-in. diameter, 24 gg, 96 feeders with side creel	CO rotor (open end) yarn to a fabric Lapique Ne 20, unfinished width (open) 224 cm, unfinished weight 358 g/m	265	300	0.16					0.19			
Kim et al. (1983)	1 kg	Knitting energy usage per unit production (kWh/kg)>no specific material; reported data 1972				1.75					0.19			
Kim et al. (1983)	1 kg	Knitting energy usage per unit production (kWh/kg)>no specific material; reported data 1980				1.29					0.19			
Collins and Aumônier (2002)	kg product	Knitting including winding for fabric for 1 pair of cotton briefs (72 g) takes 8.08 kWh/kg product				8.08					0.19			
Laursen et al. (2007)	1 kg	From Fig. 1.3, 2.3 MJ per 1 shirt of 250 g>275 g CO fabric needed				2.32					0.19			
EDIPTX	1 kg	Knitting machine	CO for a thin sweater			0.85					0.19			
IFTH2 (n.a.)	1 kg	Rib trimming holding' knitting	CO for a thin sweater			1.17					0.19			
IFTH2 (n.a.)	1 kg	Flat knitting with large panels	CO for a thin sweater			1.16					0.19			
IFTH2 (n.a.)	1 kg	Flat knitting with normal panels	CO for a thin sweater			1.17					0.19			
IFTH2 (n.a.)	1 kg	Fully fashioned flat knitting	CO for a thin sweater			4.59					0.19			
IFTH2 (n.a.)	1 kg	Seamless flat knitting	CO for a thin sweater			5.42					0.19			
IFTH2 (n.a.)	1 kg	Fully fashioned flat knitting	CO for a thick sweater			2.29					0.19			
Pretreatment	Fabric													

Table 4 (continued)

Process step/source	Quantity	Specification of process and/or extra remarks	Specification of product (CO=cotton)	Yarn count (den)	Yarn count (dtex)	Electricity (kWh)	Steam (MJ)	Natural gas (MJ)	Liquefied petroleum gas (MJ)	Diesel (MJ)	Light fuel oil (MJ)	Heavy fuel oil (MJ)	Hard coal (MJ)	Water (L)
Laursen et al. (2007) EDIPTX	1 kg	From Fig. 1.3, 2.4 MJ per 1 shirt of 250 g (fabric 275 g)	Pretreatment of fabric of 100 % CO			2.42								
Laursen et al. (2007) EDIPTX	1 kg	From Fig. 3.3, 5.2 MJ per 1 jacket of 770 g (fabric 877 g)	Pretreatment of fabric of 65 % CO+35 % PES			1.65								
Cartwright et al. (2011), Laursen et al. (2007) EDIPTX	1 kg	From Table 2, one shirt (65 % PET/35 % CO) weighs 227 g	Scouring in alkaline solution++bleaching			1.20								
Processor, 2011 phase 4	1 kg	Bleaching	40 PET/60 CO+PES staple fibers	180	200	0.40	14.4							
Processor, 2011 phase 4	1 kg	Bleaching average	40 PET/60 CO+PES staple fibers			0.50	16							
Processor, 2011 phase 4	1 kg	Bleaching	40 PET/60 CO+PES staple fibers	90	100	0.63		18						
Dyeing	Fabric													
LCA pyjama bebe IFTH	1 kg	Reactive dye for CO; PES not dyed; softening treatment during the last rinsing wash; LR=1/8	80 % CO/20 % PET, 290–300 g/m ²			1.15		31.30						104.00
Laursen et al. (2007) EDIPTX	1 kg	From Fig. 1.3, 3.3 MJ per 1 shirt of 250 g (fabric 273 g)	Reactive dye on 100 % CO			3.36								
Laursen et al. (2007) EDIPTX	1 kg	From Fig. 3.3, 9 MJ per 1 jacket of 770 g (fabric 877 g)	Dyeing of 65 % CO+35 % PES in automatic jigger			2.85								
Cartwright et al. (2011), Laursen et al. (2007) EDIPTX	1 kg	From Table 2, one shirt (65 % PET/35 % CO) weighs 227 g				1.84								
Processor, 2011 phase 5	1 kg	Dyeing	40 PET/60 CO+PES staple fibers	180	200	1.00		28.80						
Processor, 2011 phase 5	1 kg	Dyeing	40 PET/60 CO+PES staple fibers	90	100	1.25		33.75						
IPPC (2003), lowest value	1 kg	Airflow jet operating at LR 1:4.5 (CO) and 1:2–3 (PES)	Dyeing CO or PES			0.36	3.78							80.00
Table 4.28, LOW														
IPPC (2003), lowest value	1 kg	Airflow jet operating at LR 1:4.5 (CO) and 1:2–3 (PES)	Dyeing CO or PES			0.42	5.04							80.00
Table 4.28, HIGH														
Wet processing	Fabric													
Confidential source no. 7	1 kg	Wet treatment				2.73			0.38			69.90		
Confidential source no. 7	1 kg	One time washing				1.06								
Confidential source no. 8	1 kg	Subtotal scouring, dyeing, washing, softening, centrifugation	Viscose			1.14	18.32	0.00	0.00	0.00	0.00	0.00	0.00	
Laursen et al. (2007) EDIPTX	1 kg	From Fig. 1.3, 3.1 MJ per 1 shirt of 250 g (270 g fabric)	Drying final fixing+set m ² weight+softening 100 % CO			3.19								

Table 4 (continued)

Process step/source	Quantity	Specification of process and/or extra remarks	Specification of product (CO=cotton)	Yarn count (den)	Yarn count (dtex)	Electricity (kWh)	Steam (MJ)	Natural gas (MJ)	Liquefied petroleum gas (MJ)	Diesel (MJ)	Light fuel oil (MJ)	Heavy fuel oil (MJ)	Hard coal (MJ)	Water (L)
Laursen et al. (2007) EDIPTX	1 kg	From Fig. 3.3, 4.8 MJ per 1 jacket of 770 g (fabric 868 g)	Softening; drying; final fixing 65 %CO+35 % PES			1.54								
Cartwright et al. (2011), Laursen et al. (2007) EDIPTX	1 kg	From Table 2, one shirt (65 % PET/35 % CO) weighs 227 g				0.88								
Processor, 2011 phase 6	1 kg	Finishing	40 PET/60 CO+PES staple fibers	180	200	0.60		28.8						
Processor, 2011 phase 6	1 kg	Finishing	40 PET/60 CO+PES staple fibers	90	100	0.75		33.75						
IFTH2 (n.a.)	1 kg	Total	CO yarn			2.10		14.26						27.00

IFTH2 (n.a.) refers to an unpublished report named: Extrait de “aide à la prise en compte de l’environnement dans la conception d’articles textiles” par l’IFTH. Institut Francais du textile et de l’habillement

n.a. not available, LR liquor ratio

Figure 2 shows that data from Kaplan and Koç (2010) and Demir and Behery (1997) (along the lower striped line) show a considerable lower energy demand (approximately 40 %) than data from the anonymous Belgium/French factory “Processor, 2011 phase 1” (along the upper continuous line). The EDIPTX scores of ITMF (2010) and Laursen et al. (2007) were even lower than Kaplan and Koç (2010).

For the calculations in Section 4, it was decided to take the average of the two lines in Fig. 2. For extruding and spinning of polymer filament, less data are available, and it seems to be scattered, see Table 5 (under “Spinning filament”). The energy required for filament extrusion is governing the process. PET, nylon, and elastane have the same extrusion energy (CES 2012) of 6.2 MJ/kg or 1.7 kWh/kg. Note that extruding is not a function of decitex, but a function of the extrusion energy of the polymer.

3.4 Texturing of synthetic yarns

Texturing is a processing step that is applied to synthetic filaments in order to produce yarns that are more flexible, are softer, have a more natural feel, and have improved yarn recovery power. This is achieved in many ways, such as thermal and mechanical deformation of the individual filaments and their spatial arrangement in the yarn bundle.

For texturing, various technologies are being used which differ substantially in energy use. During the actual process, the feeding material (named “partially oriented yarn” [POY]) is processed into either drawn textured yarn (abbreviation is “DTY”) or air textured yarn (abbreviation is “ATY”). The old ATY machine with heated “godets” (spouts), collective drives, and water jet texturing (water and electric) was more expensive per kilogram yarn, compared to the current DTY technology (personal communication with a regional sales director from Barmag, 2011).

The energy use value for texturing (on high-end modern equipment), comes from the ITMF (2010) data and refers to a new Oerlikon Barmag machine (named “10 Barmag eFK, 240 positions”) which is based on the process of false twist texturing with manual doffing system. During the texturing process, the filament yarn is simultaneously drawn, heated, and twisted. In our calculation, we take 1 kWh/kg for texturing, being the average of the ITMF and Barmag data on texturing in Table 5, since the energy required in these machines is mainly heat to bring the material to the necessary temperature: that is, primarily a function of kilograms. Cotton yarn does not require texturing due to the natural twist of cotton.

3.5 Weaving

The energy of weaving is obviously a function of decitex; however, most of the literature does not report any information

Table 5 Manufacturing of synthetic yarn: data from literature and private communications

Process step/source	Quantity	Specification of process and/or extra remarks	Specification of product (PET=polyester)	Yarn count (den)	Yarn count (dtex)	Electricity (kWh)	Steam (MJ)	Natural gas (MJ)	Liquefied petroleum gas (MJ)	Diesel (MJ)	Light fuel oil (MJ)	Heavy fuel oil (MJ)	Hard coal (MJ)	Water (L)
Fiber+yarn manufacturing														
Pellets/flakes production	Pellets													
Cumulative energy demand, confidential study 2008	1 kg	Gate to gate				0.20		0.53	0.02	0.01	0.00			
PET production, calculation 2011, personal communication Defraye	1 kg	Nonrenewable energy use is 68.6 MJ and 2.00 kg CO ₂	Bottle grade			See specs								
PET production, calculation 2005, personal communication Defraye	1 kg	Nonrenewable energy use is 80.5 MJ and 3.30 kg CO ₂	Amorphous PET			See specs								
Spinning staple fibers														
Confidential source no. 1	Fiber													
	1 kg	Recycled PET pellets to staple fiber (or POY?)				0.89						0.48		
Confidential source no. 2	1 kg	Recycled PET flakes to staple fiber				0.52		2.21	0.02					
Confidential source no. 3	1 kg	Recycled PET pellets to staple fiber				0.31							10.57	
Confidential source no. 4	1 kg	PET flakes to staple fiber				0.69	4.75							
Defraye, 2011, personal communication	1 kg	Nonrenewable energy use is 9.4–10.5 MJ, unclear whether staple fiber, filament or mix				See specs								
IFTH1 (n.a.)	1 kg	PTA (purified terephthalic acid) and MEG (ethylene glycol) to staple fibers				4.22		0.00		53.76			14.79	
Laursen et al. (2007) EDIPTX	1 kg	Ring yarn according to formula	100 % synthetic	117	130	3.70								2,200.00
Laursen et al. (2007) EDIPTX	1 kg	According to Fig. 4.3, fiber/yarn? manufacturing of 70 %VI, 25 % PA, 5 % EL				50.62								
Spinning filament														
Barnag, 2011	Yarn													
	1 kg	PTA and MEG to filament ("direct spinning line")	POY	168	187	0.30								
Barnag, 2011	1 kg	PET pellets to filament ("extruder spinning line")	POY	168	187	0.50								
Barnag, 2011 PET extruder spinning	1 kg	PET pellets to filament ("extruder spinning line")	FDY	75	83	1.00								
Barnag, 2011	1 kg	PTA and MEG to filament ("direct spinning line")	FDY	75	83	0.80								
Brown et al. (1985)	1 kg	PET pellets to filament ("extruder spinning line")				0.64	5.00							
Confidential source no. 3	1 kg	PET pellets to filament ("extruder spinning line")	POY			1.19						0.48		
Defraye, 2011, personal communication	1 kg	Nonrenewable energy use 9.4 MJ, unclear whether staple fiber, filament or mix; estimated en. eff. improvement taken into account				See specs								

Table 5 (continued)

Process step/source	Quantity	Specification of process and/or extra remarks	Specification of product (PET=polyester)	Yarn count (den)	Yarn count (dtex)	Electricity (kWh)	Steam (MJ)	Natural gas (MJ)	Liquefied petroleum gas (MJ)	Diesel (MJ)	Light fuel oil (MJ)	Heavy fuel oil (MJ)	Hard coal (MJ)	Water (L)
Confidential source no. 5	1 kg	PET pellets to filament (“extruder spinning line”)	POY	452	500	1.50	2.20							
Confidential source no. 5	1 kg	PET pellets to filament (“extruder spinning line”)	FDY	452	500	1.70	2.20							
Texturing														
ITMF (2010)	Yarn													
1 kg	1 kg	POY to DTY, mean for 10 machines eFK with manual doffing system	POY of 125 den drawn and false twisted into a 75 den yarn of 72 filaments	75	83	1.21								
ITMF (2010) and Barmag, 2011	1 kg	Average of texturing values from ITMF and Barmag				1.00								
Barmag, 2011	1 kg	Filament to textured filament DTY (75/1.6>47 den)	Textured filament	47	52	0.7–0.9								
Barmag, 2011	1 kg	Filament to textured filament DTY (150/1.6>94 den)	Textured filament	94	104	0.5–0.6								
Confidential source no. 7	1 kg	Filament to textured filament, includes “general electricity for dyeing”	Fabric for sofa			3.75								
Confidential source no. 3	1 kg	POY to DTY	DTY			2.18								
Demir and Behery (1997)	1 kg	POY to ATY	POY	150	167	3.10								
Demir and Behery (1997)	1 kg	POY to ATY	Twofold 167 dtex POY yarn	300	334	1.80								
Confidential source no. 5	1 kg	POY to false twisted filament (including or excluding thermofixing?)	FTF			1.66								
Confidential source no. 5	1 kg	POY to air textured filament (including or excluding thermofixing?)	Air textured filament (ATY?)			3.33								
Confidential source no. 5	1 kg	POY to DTY?	DTY? (very uncertain)			2.22								

IFTH1 (n.a.) refers to an unpublished report named: Extrait de “l’Analyse de Cycle de vie pyjama Bébé” par l’IFTH. Institut Français du textile et de l’habillement
 POY partially oriented yarn, FDY fully drawn yarn, DTY drawn textured yarn, ATY air textured yarn, FTF false twisted filament, n.a. not available

Table 6 Fabric manufacturing from synthetic yarn: data from literature and private communications

Process step/source	Quantity	Specification of process and/or extra remarks	Specification of product (PET=PES=polyester; CO=cotton; PA=polyamide; VI=viscose; EL=elastan)	Yarn count (den)	Yarn count (dtex)	Electricity (kWh)	Steam (MJ)	Natural gas (MJ)	Liquefied petroleum gas (MJ)	Diesel (MJ)	Light fuel oil (MJ)	Heavy fuel oil (MJ)	Hard coal (MJ)	Water (L)
Fabric manufacturing														
ITMF (2010)	1 kg	Mean of 60 Sultex rapier weaving machines S190 N4 SP12/20, air conditioning, weaving preparation, cloth inspection, transportation units, warp beam diameter 1,000 mm, cloth beam diameter 600 mm	Fabric, 38.0/31.0 threads/cm—gray width 177 cm—gray weight 106 g/m	75	83	10.88								
Confidential source no. 7	1 kg		PES fabric for sofa			2.65			1.66		1.53			
Laursen et al. (2007) EDIPTX	1 kg	Figure 2.3	PA for jogging suit			6.73								
Knitting	Fabric													
ITMF (2010)	1 kg	Mean of 8 Mayer&Cie OV 3.2 QC circular knitting machines, 30-in. diameter, 28 gg, with side creel	Fabric interlock—unfinished width (open) 190 cm—unfinished weight 209 g/m	75	83	0.35					0.19			
IFTH1 (n.a.)	1 kg	Yarn to knitted fabric, circular knitting	80 % CO/20 % PET, 290–300 g/m ²			1.22					0.19			
Laursen et al. (2007) EDIPTX	1 kg	According to Fig. 4.3, circular knitting of 70 % VI, 25 % PA, 5 % EL (0.222 kg)				5.01					0.19			
Washing of fabric	Fabric													
Confidential source no. 7	1 kg	Unclear whether including drying; without NREU for surfactants	Fabric for sofa			0.82								
Drying of fabric	Fabric													
Confidential source no. 6	1 kg		What type of fabric? PES?			0.16		5.15						
Pretreatment	Fabric													
Laursen et al. (2007) EDIPTX	1 kg	Tot. calc. for woven PA (0.402 kg) and knitted CO (0.583 kg) for jogging suit; CO is dominant					7.1							
Laursen et al. (2007) EDIPTX	1 kg	According to Fig. 4.3, pretreatment of synth. knitted 70 % VI, 25 % PA, 5 % EL (0.222 kg)				2.19	7.9							
Dyeing	Fabric													
Laursen et al. (2007) EDIPTX	1 kg	According to Fig. 2.3, acid dye	Nylon/PA			2.56								
Laursen et al. (2007) EDIPTX	1 kg	According to Fig. 4.3, dyeing of 70 % VI (reactive), 25 % PA (acid), 5 % EL (acid) (0.222 kg)				5.63								
Thermofixing (heat setting)	Fabric													
Confidential source no. 7	1 kg		Fabric for sofa											7.95

Table 6 (continued)

Process step/source	Quantity	Specification of process and/or extra remarks	Specification of product (PET=PES=polyester; CO=cotton; PA=polyamide; VI=viscose; EL=elastan)	Yarn count (den)	Yarn count (dtex)	Electricity (kWh)	Steam (MJ)	Natural gas (MJ)	Liquefied petroleum gas (MJ)	Diesel (MJ)	Light fuel oil (MJ)	Heavy fuel oil (MJ)	Hard coal (MJ)	Water (L)
Finishing Laursen et al. (2007) EDIPTEX	Fabric 1 kg	Tot. calc. for woven PA (0.402 kg) and knitted CO (0.583 kg) for jogging suit; CO is dominant				1.97								
Laursen et al. (2007) EDIPTEX	1 kg	According to Fig. 4.3, finishing, drying, final fixing+set m ² weight of 70 % VI, 25 % PA, 5 % EL (0.222 kg)				2.50								

IFTH1 (n.a.) refers to an unpublished report named: Extrait de “l’Analyse de Cycle de vie pyjama Bébé” par l’IFTH. Institut Français du textile et de l’habillement

on yarn size (see Table 3). Figure 3 shows the required electricity as a function of 1/tex for cotton. For weaving, there is rather a big uncertainty: the anonymous factory (“Processor, 2011 phase 3”) reports a doubling in energy consumption, compared to machine manufacturing data.

It is not expected that data on weaving polymers will deviate much from the data on weaving cotton. The ITMF (2010) reference (under “Weaving”) in Table 6 fits the lower line of Fig. 3, which is 11 kWh/kg for 83 dtex ($=0.12 \times 1/\text{tex}$). For the calculations in Section 4, it was decided to take the average of the two lines in Fig. 3.

3.6 Knitting

The energy required for knitting is considerably lower (approximately a factor of 20) than for weaving (compare, e.g., the values of ITMF 2010 in Tables 3 and 4). Knitting is, therefore, a better solution in terms of environmental burden. Elaborating on the data analysis for weaving, it is assumed that the energy consumption for knitting is proportional to 1/dtex as well, as illustrated by the line in Fig. 4.

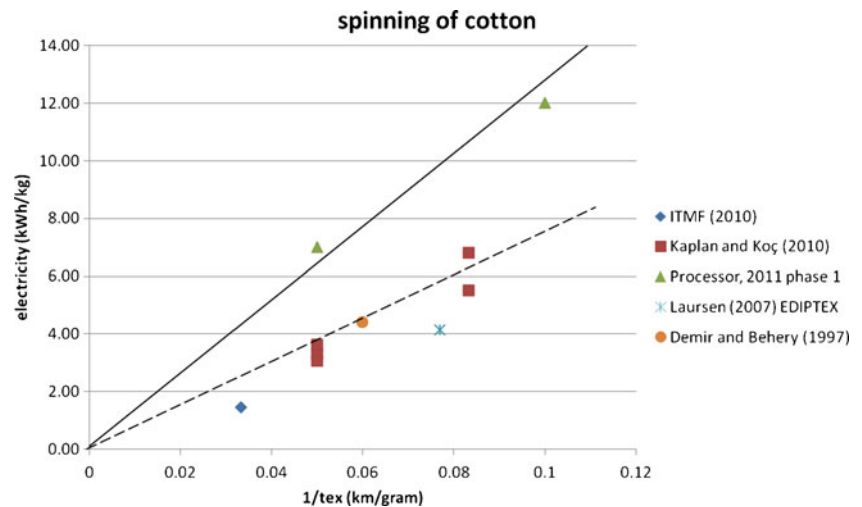
3.7 Pretreatment of cotton fabric and thermofixing of polymers

Pretreatment of cotton comprises several wet operation steps (singeing, desizing, scouring, mercerizing, and bleaching) in order to prepare the fabric for dyeing. The decision to apply one or the other depends on the required grade of the end product. Scouring and bleaching are typically required for men’s shirts since they are mostly of a lighter color. Scouring (also known as boiling-off or kier boiling) is aimed at the extraction of impurities present on the raw fiber or picked up at a later stage (IPPC 2003). Bleaching removes all natural color. Both processes are included in the values for the pretreatment of cotton shown in Table 4. The data come from Laursen et al. (2007), Cartwright et al. (2011), and the Belgian processor of shirt material (“Processor, 2011 phase 4” in the table).

For the calculation in Section 4, the average (0.5 kWh electricity and 16 MJ steam) of the data of “Processor, 2011 phase 4” in Table 4 has been applied. Typical pretreatment operations before coloring of synthetic fabrics are washing and thermofixing (heat setting). Heat setting of fabric increases the density of the fabric, avoids crimp later on (production and use), and enables dye fixation. This heat setting process on fabric must not be confused with the thermofixation of the fiber during texturing (which is normally processed at a lower temperature).

The IPPC (2003) report mentions heat setting temperatures ranging from 150 to 205 °C at different mills. In the calculations of Section 4, we apply 7.9 MJ heat/kg, according to the EDIPTEX score of Laursen et al. (2007), second line under “Pretreatment” in Table 6.

Fig. 2 Spinning of cotton: electricity demand as a function of 1/dtex



4 Results cradle-to-gate for greige textile

4.1 Cotton greige textile cradle-to-gate of the factory

Calculations have been made for cradle-to-gate (of the fabric dyeing factory) for 70, 100, 150, 200, and 300 dtex (1 dtex=0.84 den) woven material, for the process steps defined in Section 2.2, excluding dyeing and final finishing (see Figs. 5, 6, 7, and 8).

Figure 5 shows the eco-costs (in Euros per kilogram textile) for the fiber manufacturing, spinning, weaving, and pretreatment of cotton textiles. Figures 6 and 7, respectively, present the CO₂ equivalent values (in kilograms per kilogram) and the CED (in megajoules per kilogram) scores for the same processes. Finally, Fig. 8 shows the ReCiPe scores (in points) for greige cotton fabric. All indicators show that the thinner the yarn, the higher the environmental pollution per kilogram. The underlying datasets for the calculations leading to these figures are presented in Table 7. The Idemat database which is mentioned in Table 7 is based on Ecoinvent data and is open

access for Ecoinvent license holders. Midpoint and endpoint calculations are open access (Idemat 2012).

A remarkable conclusion for yarn sizes less than 150 dtex is that the spinning and weaving energy seem to play a major role in the eco-burden of the woven material, rather than the production of cotton fiber. Another conclusion is that, in the eco-costs and the ReCiPe indicator, cotton production plays a relatively more important role than in the CED and CO₂ indicators, being a result of the fact that ecotoxicity and human toxicity are included in the first and the last indicators, see Section 2.1.

4.2 Synthetic greige textile cradle-to-gate of the factory

Calculations have been made for cradle-to-gate (of the fabric dyeing factory) for acryl, nylon, PET, and elastane (70 dtex=58 den) woven material, for the process steps defined in Section 2.2, excluding dyeing and finishing (see Figs. 9, 10, 11, and 12). The underlying datasets for the calculations leading to these figures are presented in Table 7.

Fig. 3 Weaving of cotton and polymer fibers: electricity demand as a function of 1/dtex

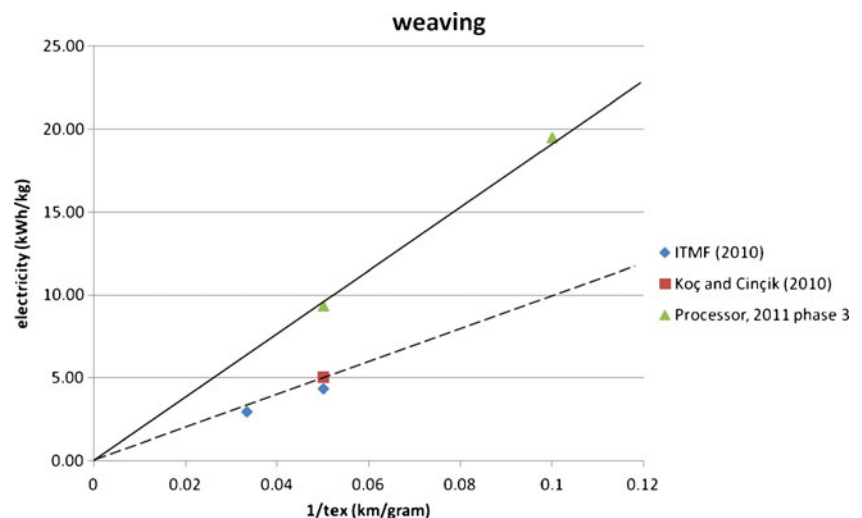


Fig. 4 Knitting: electricity demand as a function of 1/dtex

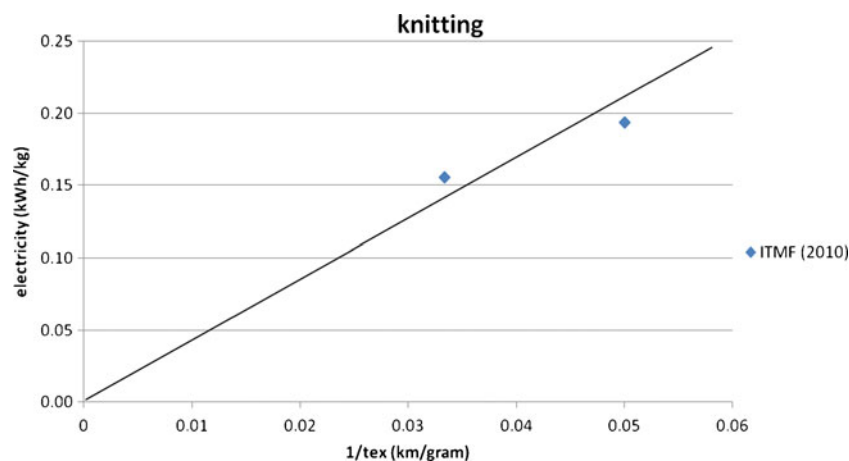


Figure 9 shows the eco-costs (in Euros per kilogram textile) for polymer pellet production, extruder spinning, texturing, weaving, and heat setting of synthetic textiles. Figures 10 and 11, respectively, present the CO₂ equivalent values (in kilograms per kilogram) and the CED (in megajoules per kilogram) scores for the same processes. Finally, Fig. 12 shows the ReCiPe scores (in points) for greige synthetic fabric. All figures show that, for woven fabric of 70 dtex yarn, acryl and PET textile have the best environmental scores and nylon textile is the most polluting.

5 Dyeing and finishing of fabric

5.1 LCI data—gate-to-gate for dyeing and finishing

The data for dyeing are highly case dependent:

1. Consumption and emission levels for dyeing are strongly related to the type of fiber, the makeup, the dyestuff, the dyeing technique, and the machinery employed (IPPC 2003).

2. Processing and formulas for dyeing are related to the quality requirements.
3. Process parameters are reaction type, availability of chemicals, time, temperature, and pH (Tobler-Rohr 2011).

All previously mentioned variables lead to an enormously wide range of processes and consequently also of energy use. There are some general rules regarding the type of dyestuff used per type of fiber (Tobler-Rohr 2011): PET is dyed with disperse dyestuffs (if acid and alkaline are used for PET, this results in a lower grade). Cotton is dyed with reactive dyestuffs (and vat, direct, or sulfur dyestuffs are also applied). Nylon can be dyed with disperse, metal complex, and acid dyestuffs. The usage of dye carriers for dyeing PET has been the subject of research and discussion for a long time. Yeh and Smith (1983) reported about the toxicity and volatility of this group of chemicals when used for dyeing processes. Several other references, e.g., the BATBREF report (IPPC 2003) and Yang and Li (1999) point out the dangers of dye carriers as well. No data could be found on how widespread these chemicals are applied today, but dye carriers are still used in many dyeing houses around the world. The IPPC (2003) report mentions that one of the best available technologies

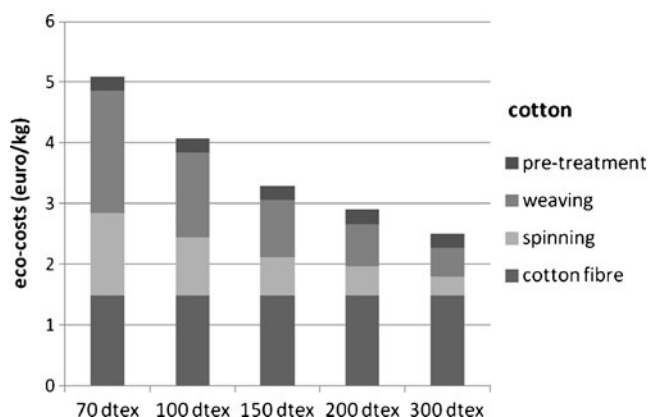


Fig. 5 The eco-costs of cotton textiles

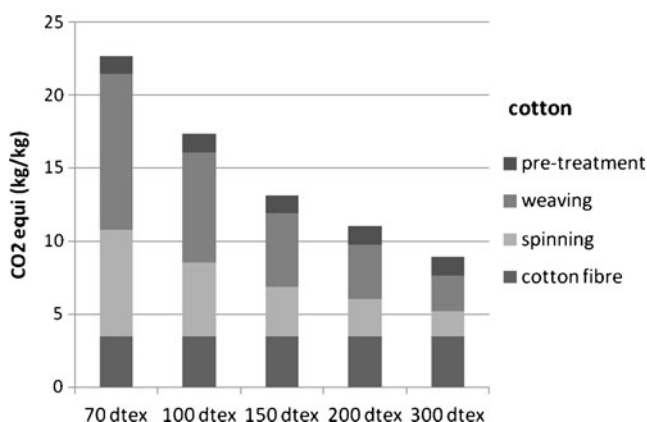


Fig. 6 The carbon footprint of cotton textiles

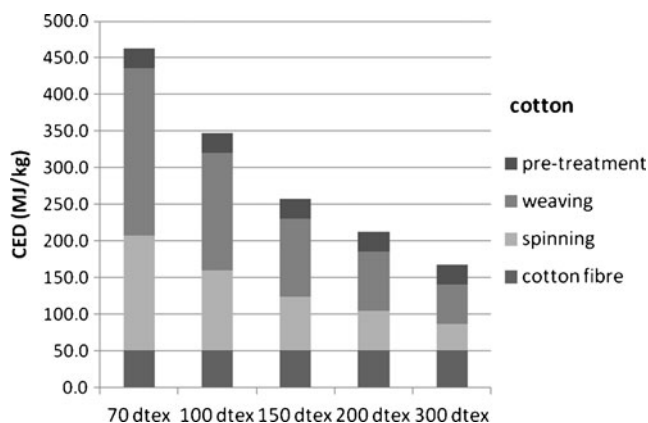


Fig. 7 The CED of cotton textiles

for dyeing of PET and cotton is the airflow jet machine and reports electricity input values for dyeing PET and cotton, with the range for the liquor ratio depending on the type of material (1:2–1:3 for PET and 1:4.5 for cotton).

After dyeing, a range of process steps are executed, depending on the desired fabric properties. Final finishing processes can, for example, consist of special treatments with flame retardants, softeners, easy care finishing, etc. Every extra step is likely to require the usage of chemicals and auxiliaries. Different bath temperatures, liquor ratios, and/or extra washing cycles are required. A thermofixation step could be part of final finishing as well.

References on final finishing processes report datasets which consist of very different process steps (if specified at all), and in addition, large ranges are found for comparable process steps. The toxic emissions of dyeing and final finishing have been analyzed for a best practice production facility in the Netherlands, based on the Dutch emission database. This production facility is Global Organic Textile Standard-certified and Oeko-tex-certified (an independent testing and certification system for textile raw materials, intermediate, and end products at all stages of production), the effluents are processed in water

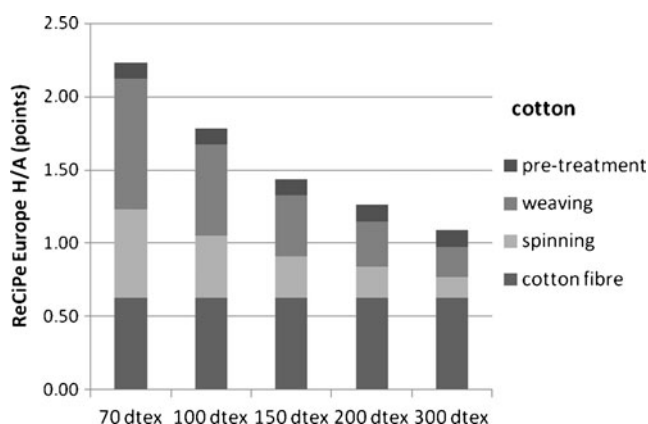


Fig. 8 The ReCiPe score (“Europe H/A”) of cotton textiles

treatment plants, and emissions to air are minimized. Results are shown in Section 5.2. Although many West European facilities reach similar high standards, the reader must keep in mind that such standards are not common in other textile-producing countries outside of Europe, like, for example, India and China.

5.2 Results gate-to-gate for dyed and finished fabric

This section gives value ranges for the final processing steps (dyeing and finishing) for woven or knitted material, gate-to-gate. The first gate refers to the exit of the greige fabric from the material processing factory and the second gate refers to the entry of the textile to the product manufacturing factory.

The ranges of the single indicators were calculated based on the data in Tables 4 (for cotton) and 6 (for synthetics). Since the dyeing and final finishing processes often take place at one production site, the separate values per process step in Tables 4, 5, and 6 are added up and presented in the succeeding paragraphs. The lowest total score is found for Cartwright et al. (2011), and the highest total score is found for Processor, 2011 phases 5 and 6. The EDIPTX scores of Laursen et al. (2007) are found in between. For the other data sources, we miss either data on dyeing or on finishing.

The value ranges of the single indicators for the energy required for dyeing and finishing of 1 kg cotton textile are:

- Eco-costs, €0.26–0.95;
- CO₂ equivalent, 1.39–6.08 kg CO₂ equivalent;
- CED, 30–108 MJ;
- ReCiPe, 0.12–0.54 Pt.

Note that some values are for dyeing of cotton blends (mixtures with other materials, e.g., PET), but cotton is always dominant. Fiber blends need to be dyed sequentially, for instance, separately for cotton dyeing and then PET dyeing. Therefore, values of dyeing of blends are larger than values of dyeing of pure cotton (and can reach twice the value).

The ranges of the single indicators for the energy required for dyeing and finishing of 1 kg synthetic textile are:

- Eco-costs, €0.43–0.77;
- CO₂ equivalent, 2.31–4.14 kg CO₂ equivalent;
- CED, 50–89 MJ;
- ReCiPe, 0.20–0.35 Pt.

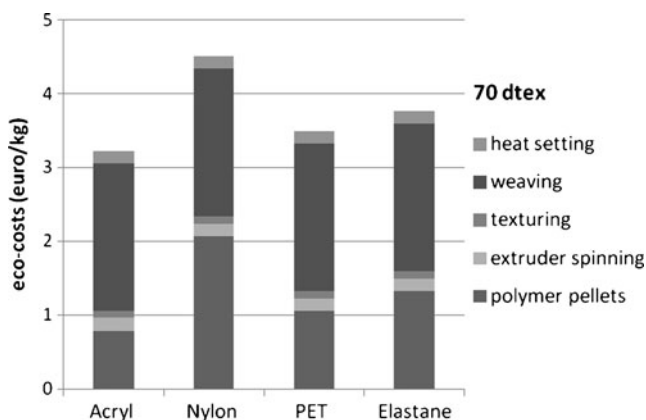
The single indicators of the toxic emissions of the production facilities must be added. These toxic emissions are publicly available at the Dutch emission database for production facilities in the Netherlands. The toxic emissions of the best practice manufacturer mentioned in Section 5.1 are given in Table 8. This table shows the emission of a chemical substance (in kilograms per year), the eco-costs of that substance (in Euros per kilogram), the eco-costs of the emission (in

Table 7 LCA data used in Figs. 5, 6, 7, 8, 9, 10, 11, and 12

Ecoinvent LCI name or Idemat 2012 LCI name	Eco-costs	CO ₂	CED	ReCiPe
Acetonitrile, at plant/RER	0.753	3.040	86.7	0.362
Cotton fibers, ginned, at farm/CN	1.481	3.474	50.4	0.628
Polyurethane, flexible foam, at plant/RER	1.324	4.836	103.1	0.517
Nylon: nylon 6, at plant/RER 50 % + nylon 66, at plant/RER 50 %	2.069	8.638	129.7	0.780
Polyethylene terephthalate, granulate, amorphous, at plant/RER	1.057	2.698	78.4	0.346
Dyeing, excluding pigments and carriers (Section 3.6)	0.422	2.245	48.2	0.199
Heat setting and washing synthetic fabrics (Section 3.5)	0.171	0.908	19.5	0.081
Knitting 83 dtex (electricity 0.51 kWh/kg, see Fig. 3)	0.048	0.257	5.5	0.021
Knitting 200 dtex (electricity 0.21 kWh/kg, see Fig. 3)	0.020	0.106	2.3	0.009
Knitting 300 dtex (electricity 0.14 kWh/kg, see Fig. 3)	0.013	0.071	1.5	0.006
Pretreatment of cotton (Section 3.5)	0.237	1.261	27.1	0.105
Spinning cotton 45 dtex (electricity 22.4 kWh/kg, see Fig. 1)	2.127	11.322	243.2	0.942
Spinning cotton 70 dtex (electricity 14.4 kWh/kg, see Fig. 1)	1.368	7.281	156.4	0.605
Spinning cotton 150 dtex (electricity 6.73 kWh/kg, see Fig. 1)	0.638	3.396	72.9	0.282
Spinning cotton 300 dtex (electricity 3.37 kWh/kg, see Fig. 1)	0.319	1.700	36.5	0.141
Spinning extruder polymer filaments (80–500 dtex) (Section 3.2)	0.168	0.896	19.2	0.074
Spinning viscose fibers (80–500 dtex) (Section 3.2)	0.042	0.223	4.8	0.019
Texturing polymer fibers (Section 3.3)	0.095	0.505	10.8	0.042
Weaving 45 dtex (electricity 32.9 kWh/kg, see Fig. 2)	3.118	16.595	356.4	1.380
Weaving 70 dtex (electricity 21.1 kWh/kg, see Fig. 2)	2.004	10.667	229.1	0.887
Weaving 150 dtex (electricity 9.87 kWh/kg, see Fig. 2)	0.936	4.980	106.9	0.414
Weaving 300 dtex (electricity 4.93 kWh/kg, see Fig. 2)	0.467	2.488	53.4	0.207

Euros per year), and the eco-costs of 1 kg of fabric (in Euros per kilogram). The total eco-cost of the toxic emissions of this best practice manufacturer is round €0.029/kg.

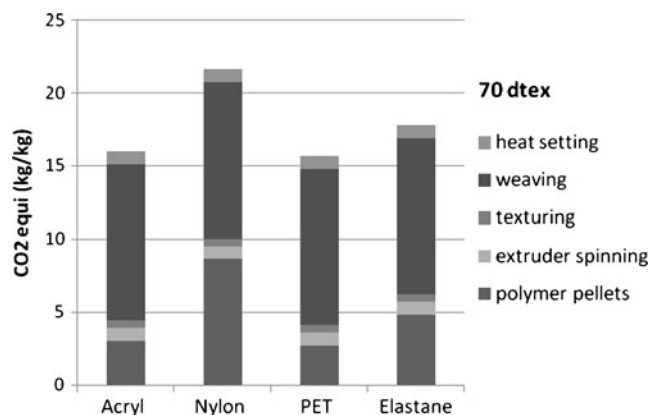
The best practice of Table 8 is not unique in the Netherlands: there are more manufacturers who reach similar green production standards. The situation in other countries like India and China is not known, however, since the environmental law is less stringent (or even absent) and the emissions are, therefore, not measured. The level of pollution can easily be a factor of 10 higher in these countries.

**Fig. 9** The eco-costs of synthetic textiles, 70 dtex

6 The use phase and end-of-life

6.1 Use phase

The main environmental impacts in the use phase are caused by the washing, drying, and ironing of the garments. Several studies and reports (e.g., Collins and Aumônier 2002; Steinberger et al. 2009; BSR 2009), which include the use phase in the assessment, identify this phase as the most important in terms of energy use and carbon dioxide emissions. When interpreting the results, it

**Fig. 10** The carbon footprint of synthetic textiles, 70 dtex

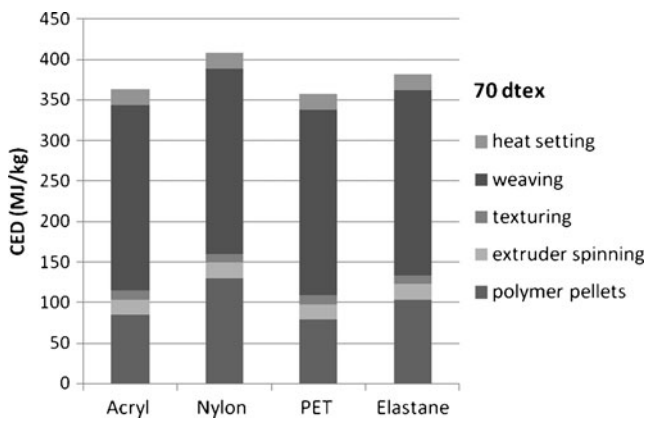


Fig. 11 The CED of synthetic textiles, 70 dtex

should, however, be considered that the outcome may vary substantially depending on the concrete circumstances. It is extremely difficult to determine the way the consumer wears and takes care of different clothing products. No literature data or empirical studies on wearing and laundry behavior of garments could be found. Literature data on the use phase are presented in Table 9.

It appears that user behavior has changed considerably in the last decennium:

- Ever more users tend to wash at lower temperature, i.e., 40 °C, rather than an average temperature of 60 °C as assumed in older studies.
- Most users in the EU buy “label A” washing machines and dryers.

According to Steinberger et al. (2009)), the reduction of washing temperature from 60 to 40 °C saves approximately 40 % electricity. According to the European energy consumption

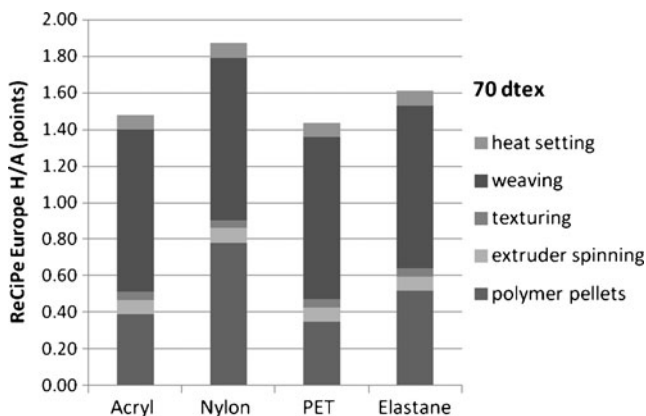


Fig. 12 The ReCiPe score (“Europe H/A”) of synthetic textiles, 70 dtex

labeling scheme (EU Directive 92/75/EC), the energy consumption of an “energy label A” washing machine is (less than) 0.19 kWh for 6 kg laundry at 60 °C, so 0.11 kWh/6 kg laundry at 40 °C.

The single indicators for 50 times washing, 1 kg laundry, 40 °C, 0.917 kWh (3.3 MJ) electric energy, low voltage are:

- Eco-costs, €0.096;
- CO₂ equivalent, 0.52 kg CO₂ equivalent;
- CED, 11.2 MJ;
- ReCiPe, 0.043 Pt.

The energy consumption of dryers is considerably more than washing machines. An “energy label A” drying machine has an electricity consumption of (less than) 0.55 kWh/6 kg, which is 4.6 kWh (16.5 MJ)/kg for 50 drying cycles.

The single indicators for 50 times drying, 1 kg laundry, 16.5 MJ electric energy, low voltage are:

- Eco-costs, €0.48;
- CO₂ equivalent, 2.6 kg CO₂ equivalent;
- CED, 56 MJ;
- ReCiPe, 0.21 Pt.

6.2 The end-of-life

At their end-of-life phase, garments in Western Europe are either burned in a municipal waste incinerator or collected via the recycling bin. In the Netherlands (year 2000), 67 % ends up in a municipal waste incinerator and 33 % ends up in a recycle bin (in the Netherlands, there is virtually no textile in landfills). Of the recycled material, 20 % is wearable and exported to developing countries and 13 % is not wearable. This 13 % is downcycled in several low-value materials (Verhulst 2010). A new development is the mechanical or chemical recovery of the fibers from the fabric material, from which new high-quality textile can be woven. Accurate data for these upcycling processes of the materials under study are not yet available.

Cotton has a credit when it is incinerated with heat recovery, since the carbon is bio-based. The credit is based on “system expansion” in LCA and the fact that biogenic CO₂ emissions are not counted in LCA. It is related to the avoidance of fossil fuels and depends on the efficiency of the system. For a modern municipal waste incinerator, with an electric production efficiency of 25 %, the credit is estimated at eco-costs, –€0.11/kg; carbon footprint, –0.60 kg CO₂ equivalent/kg; CED, –15 MJ; ReCiPe, –0.051 Pt/kg. Note that these scores are negative since it is a credit (related to the delivery of electricity). Note also that such a rather high credit does not exist for fossil-based polymers, since the eco-burden of the emitted fossil CO₂ is of the same magnitude as the credit of the delivered electricity. Data

Table 8 Emissions of a best practice production plant for dyeing and finishing in the Netherlands, 150,000 kg/year

Substance	Emissions (kg/year)	Eco-costs emissions (€/kg)	Eco-costs emissions (€/year)	Eco-costs textile (€/kg)
Benzene	4.31	2.11	9.10	0.0001
Ethene	43.08	9.70	417.87	0.0028
Particulates, <10 µm	3.20	15.88	50.83	0.0003
Particulates, <2.5 µm	3.20	29.65	94.88	0.0006
Fluoranthene	0.01	0.93	0.01	0.0000
Carbon monoxide, fossil	95.80	0.26	25.07	0.0002
Methane	258.50	3.38	872.44	0.0058
Non-methane VOC*	172.30	5.74	989.00	0.0066
Nitrogen oxides	400.60	4.62	1,850.77	0.0123
Toluene	8.62	6.20	53.41	0.0004
Sulfur oxides	4.83	8.25	39.85	0.0003
Total eco-costs			4,403.22	0.0294

*VOC volatile organic compounds

for combustion with heat recovery of cotton and polymers can be found in Idemat (2012).

7 Overview over the textile life cycle

Figures 13 and 14 give a final overview of the breakdown of the environmental burden over the textile life cycle. These diagrams show the total eco-costs for a woven textile product made out of cotton, PET, nylon, acryl, or elastane with yarn thicknesses of 70 dtex (Fig. 13) and 300 dtex (Fig. 14).

Figure 13 makes clear that the environmental performance of woven cotton textile products (70 dtex) is the worst, followed by (in order of magnitude) nylon, elastane, and PET. Acryl textile products represent the least eco-costs, and it can be concluded from this analysis that acryl textiles have the best environmental profile for the given specifications.

Note that the environmental burden is reduced at a higher yarn size due to the decrease in energy use for the spinning and weaving processes of thicker yarns (as described in Sections 3.3 and 3.5 and likewise in Section 3.6 for knitting). For example, as shown in Fig. 14, the total eco-cost for yarn of 300 dtex reduces by 24 % (for nylon) to 38 % (for cotton). As a consequence, cotton and nylon change places (a nylon textile product made out of 300 dtex yarn has higher eco-costs than one made out of cotton) and the ranking of the other materials stays the same (acryl is best, followed by PET and elastane).

In contrast with the outcomes of several other studies (e.g., BSR 2009; Collins and Aumônier 2002; Cotton 2011), Figs. 13 and 14 do not indicate the use phase as a primary “hot spot” for environmental burden. For thicker yarns, the share of the use

phase in the total eco-costs will increase for obvious reasons, but will not become too important (for acryl textile of 70 dtex, the use phase represents 11 % of the total eco-costs and, for 300 dtex, this becomes 16 %). This analysis rejects the classical conclusion which identifies washing and drying during the use phase as the most significant life cycle stage for textile products and shifts the emphasis on the manufacturing processes.

8 Discussion and conclusions

8.1 Discussion

While the textile and fashion industry seem to concentrate their environmental decisions on the choice of the base material, this paper points out that much can be improved by selecting the right fabric specifications. Note that the right choice should always take into account the intended design and quality in terms of haptics (“touch”), insulation properties (warmth), and durability of the product.

The best choice from an environmental point of view is to use a knitted fabric (compare Figs. 3 and 4). Based on Figs. 2, 3, and 4, it could be easily concluded that it is better to use a thicker yarn, but this conclusion provokes the discussion whether to analyze the pollution of textiles per kilogram fabric or per square meter of fabric. Table 10 gives an overview. A heavier textile is more polluting per square meter, but has different physical properties than a lighter material. An example is the technical life span of woven textile, which is proportional to the thickness of the fiber (Manich et al. 2001). In applications where the textile is used

Table 9 Share of environmental impacts across the value chain

	Product studied	Use phase	Share of total primary energy use					
			Manufacturing	Washing	Drying	Ironing	Other	Total
Steinberger et al. (2009)	Cotton T-shirt	50 washes	27 %	26 %	47 %	0 %	0 %	100 %
Collins and Aumônier (2002) ¹⁾	Polyester trousers (0.4 kg)	92 washes	20 %	32.5 %	17 %	12 %	18.5 %	100 %
Collins and Aumônier (2002) ¹⁾	Men's cotton briefs (0.216 kg)	104 washes	16 %	40 %	38.5 %	0 %	5.5 %	100 %
Cotton Incorporated (2011)	Knit cotton golf shirt (1.0 kg) ²⁾	Average ³⁾	16 % (approx. 190 MJ/kg)	84 % (approx. 1,000 MJ/kg)				100 %
Cotton Incorporated (2011)	Knit cotton golf shirt (1.0 kg) ²⁾	Best ³⁾	49 % (approx. 190 MJ/kg)	51 % (approx. 200 MJ/kg)				100 %
Cotton Incorporated (2011)	Knit cotton golf shirt (1.0 kg) ²⁾	Worst ³⁾	7 % (approx. 190 MJ/kg)	93 % (approx. 2,500 MJ/kg)				100 %
Smith and Barker (1995)	Polyester blouse (0.054 kg)	40 washes/94 °F+drying	18 % (approx. 305 MJ) ^{4a)}	55 %	27 %	0 %	0 %	100 %
Smith and Barker (1995)	Polyester blouse (0.054 kg)	40 washes/cold no drying	98 % (approx. 305 MJ) ^{4b)}	2 %	0 %	0 %	0 %	100 %
BSR (2009) ⁵⁾	All clothing types	Aggregated	61 %	13 %	9 %	17 %		100 %
BSR (2009) ⁶⁾	n.a.	Warm wash	n.a.	30 %	52 %	18 %		100 %
BSR (2009) ⁶⁾	n.a.	Cold wash	n.a.	6 %	70 %	24 %		100 %
BSR (2009) ⁷⁾	Denim jeans	104 washes	43 %		57 %			100 %

GHG greenhouse gas, *n.a.* not available

¹⁾ Prepared by Environmental Resources Management (2002) for Marks & Spencer

²⁾ Very similar results for a pair of woven cotton trousers

³⁾ Average, 54 % cold wash/46 % heated wash; load size, medium; washer efficiency, 70 % conventional/30 % Energy Star; water heater type, 50 % elec./50 % nat. gas. Drying, 84 % dryer/16 % air dry; dryer efficiency, 70 % conventional/30 % Energy Star. Best, 100 % cold wash; load size, extra large; washer efficiency, 100 % Energy Star; water heater type, 100 % nat. gas; drying, 100 % air dry; dryer efficiency, n/a. Worst, 100 % heated wash; load size, small; washer efficiency, 100 % conventional; water heater type, 100 % elec.; drying, 100 % electric dryer; dryer efficiency, 100 % conventional

^{4a)} According to Fig. 2, the total energy requirements=1,607.4 million Btu=1,607×0.00154 MJ=1,694 MJ. This means 100 % is 1,694 MJ and subsequently 18 % represents 305 MJ

^{4b)} Baseline washing temperature is 94 °F>when washing cold and no drying according to Fig. 11 the total energy for one laundry (=1.08 kg fabric) is 4,000 Btu~5.7 MJ~2 % of 305 MJ

⁵⁾ Chart 3: use phase care options: comparative GHG emissions per event; several sources

⁶⁾ Chart 1: aggregate clothing life cycle GHG emissions

⁷⁾ Chart 6: source: Levi's Strauss

until it is worn out, the functional unit should include the aspect of the maximum life span and should be per square meters per year. The best choice then is to take a heavier textile because a thick fabric lasts longer.

From a life cycle perspective, much more research is required on the use phase, especially with regard to consumer behavior. For shirts, the assumption of 50 washes (as given in the literature) seems to be reasonable. However, trousers seem

to be washed less often, say 15 to 20 washes, but no data are available. For party dresses, one to three washes seem to be a reasonable choice. The consumer behavior with regard to the use of drying machines also needs further research, since it seems that not all washes are dried in a machine.

The data presented in this report is subject to large uncertainties. This is partly a consequence of purely conducting the analysis on the basis of openly available data and voluntary

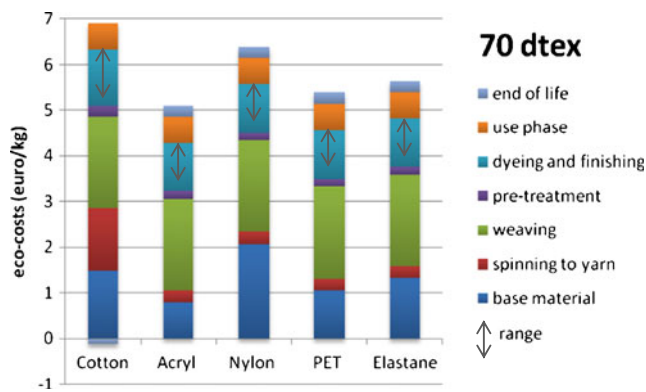


Fig. 13 The eco-costs over the life cycle for a woven textile product, 70 dtex

contributions of companies. A further reason for the large uncertainties is the nature of (parts of) the textile sector which is characterized by very diverse products and practices. Dyeing and final finishing processes are strongly case dependent, as well as the scenarios on the use phase and end-of-life. On top of this, there is a lack of data on wearing and laundry behaviors of consumers. The authors expect that the results presented in this article will hopefully be subject to further discussion, where the size of the yarn will be taken into account.

8.2 Conclusions

From the data tables, it can be concluded that the energy consumption per kilogram yarn is inversely proportional to the yarn size in decitex (i.e., the energy consumption per kilogram is proportional to the length). The energy of weaving and knitting is obviously a function of decitex as well, but most of the references do not specify the yarn count when they present energy data for these processes. LCA research on textiles can only be accurate when yarn thickness (e.g., in decitex or denier)

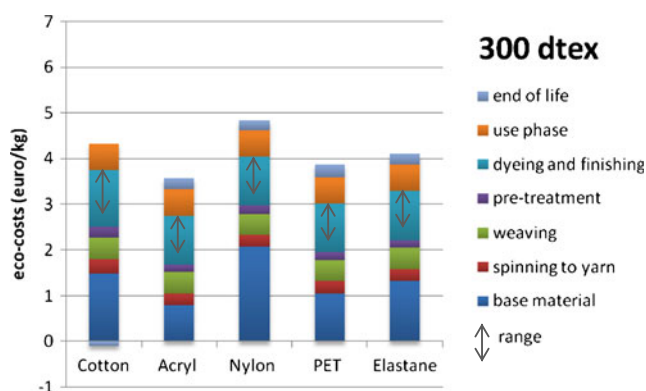


Fig. 14 The eco-costs over the life cycle for a woven textile product, 300 dtex

Table 10 Eco-costs of woven greige synthetic textile as a function of yarn thickness

Yarn thickness (dtex)	Eco-costs (€/kg)	Density (kg/m ²)	Eco-costs (€/m ²)
70	4.508	84	0.379
150	3.439	180	0.619
300	2.971	361	1.072

is specified. In case the functional unit indicates the fabric per square meter, the density (in grams per square meter) must also be known.

The cradle-to-gate analysis of the production chain from raw material extraction to manufactured textile demonstrates that acryl and PET have the least impact on the environment (followed by elastane and nylon). Cotton represents the highest environmental burden in all four single indicators (CO₂ equivalent, CED, Eco-costs 2012, and ReCiPe). For cotton fabric less than 150 dtex, weaving and spinning have the highest cradle-to-gate impact. For polymer fibers, the impact of spinning is comparatively low; however, weaving has the highest impact in less than 70 dtex textile production. Knitting has a factor of 20 lower impact than weaving for all fibers, so knitting is a better solution than weaving from an environmental point of view.

Dyeing and final finishing processes are case dependent, but calculations suggest ranges that do not exceed one third of the total of the preceding cradle-to-gate processes. The cradle-to-grave analysis in eco-costs for a woven textile, made out of 70 dtex yarn, shows that a cotton product has the worst environmental profile and a product made out of acryl the best. For the given specifications, weaving is the most significant life cycle stage followed by the manufacturing of the base material (and spinning for cotton). The total environmental burden over the complete life cycle is reduced at a higher yarn size due to the decrease in energy use (per kilogram textile) for the spinning and weaving processes of thicker yarns. As a consequence, the impact of weaving (and likewise of knitting) becomes less important and cotton and nylon change places in the ranking (breakeven point is around 100 dtex). In the use phase, the washing and drying of laundry has less relative impact than it is suggested in the classical literature (e.g., Laitala and Boks 2012; Collins and Aumônier 2002; BSR 2009), even when thicker yarns are used to manufacture the textile product, provided that “energy label A” machines are used.

LCA results of textile products over the whole value chain are highly case dependent, especially when the dyeing and finishing processes and the use phase and end-of-life are included in the analysis. Further LCI data studies on textiles and garments are urgently needed to lower the current uncertainties in LCA of textile materials and products.

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References

- Bahr Dar Textile Share Company (2010) Promoting resource efficiency in small and medium sized enterprises BD-Textile-Final-RE-Plan. UNEP Division of Technology, Industry and Economics
- Brown HL, Hamel BB, Hedman BA (1985) Energy analysis of 108 industrial processes. US Department of Energy, pp 207–209
- BSR (2009) Apparel industry life cycle carbon mapping. Business for Social Responsibility
- Cartwright J, Cheng J et al (2011) Assessing the environmental impacts of industrial laundering: life cycle assessment of polyester/cotton shirts. M.Sc. thesis, Bren School of Environmental Science & Management, University of California
- CES (2012) Cambridge engineering selector. Granta Design, Cambridge
- Collins M, Aumônier S (2002) Streamlined life cycle assessment of two Marks & Spencer plc apparel products. Environmental Resources Management, Oxford
- Cotton Incorporated (2011) Life cycle assessment of cotton fibre and fabric executive summary (15 pages) and brochure (4 pages). Prepared for Vision 21 (A Project of the Cotton Foundation)
- Dahlöf L (2004) LCA methodology issues for textile products. Technical report no. 2004:8. Licentiate thesis, Chalmers University of Technology, Göteborg
- Demir A, Behery HM (1997) Synthetic filament yarn: texturing technology. Prentice Hall, Englewood Cliffs
- Ecoinvent (2007a) Life cycle inventories of renewable materials. The Swiss Centre for Life Cycle Inventories
- Ecoinvent (2007b) Life cycle inventories of chemicals. The Swiss Centre for Life Cycle Inventories
- Ecoinvent (2007c) Strommix and Stromnetz. The Swiss Centre for Life Cycle Inventories
- Ecoinvent (2010) Database Ecoinvent version v2.2. The Swiss Centre for Life Cycle Inventories
- Goedkoop M, Hofstetter P, Müller-Wenk R, Spriensma R (1998) The Eco-indicator 98 explained. *Int J Life Cycle Assess* 3(6):352–360
- Idemat (2012) Database Idemat version 2012, Delft University of Technology. Available at <http://www.ecocostsvalue.com/EVR/model/theory/subject/5-data.html>
- IPPC (2003) Reference document on best available techniques (BAT) for the textiles industry. Integrated Pollution Prevention and Control (IPPC), European Commission
- ITMF (2008) International production cost comparison. International Textile Manufacturers Federation, Zürich
- ITMF (2010) International production cost comparison. International Textile Manufacturers Federation, Zürich
- Kalliala E, Talvenmaa P (1999) Environmental profile of textile wet processing in Finland. *J Clean Prod* 8:143–154
- Kaplan E, Koç E (2010) Investigation of energy consumption in yarn production with special reference to open-end rotor spinning. *Fibres Text East Eur* 18(79):7–13
- Kim SY, Grady PL, Hersh SP (1983) Energy consumption and conservation in the fibre producing and textile industries. *Text Prog* 13(3):1–14
- Koç E, Çinçik E (2010) Analysis of energy consumption in woven fabric production. *Fibres Text in East Eur* 18(79):14–20
- Laitala K, Boks C (2012) Sustainable clothing design: use matters. *J Des Res* 10(1/2):121–139
- Laursen SE, Hansen J et al (1997) Environmental assessment of textiles. Environmental Project No. 369, Danish Environmental Protection Agency
- Laursen SE, Hansen J et al (2007) EDIPTEX—environmental assessment of textiles. Working Report No. 24, Danish Technological Institute
- Manich AM, de Castellar MD, Sauri RM, Miguel RAL, Barella A (2001) Abrasion kinetics of wool and blended fabrics. *Text Res J* 71(6):469–474
- Mestre A, Vogtlander J (2013) Eco-efficient value creation of cork products: an LCA-based method for design intervention. *J Clean Prod*. doi:10.1016/j.jclepro.2013.04.023
- Palamutcu S (2010) Electric energy consumption in the cotton textile processing stages. *Energy* 35(7):2945–2952
- Shen L (2011) Bio-based and recycled polymers for cleaner production—an assessment of plastics and fibres. Ph.D. thesis, Department of Science, Technology and Society (STS)/Copernicus Institute, Utrecht University
- Smith GG, Barker RH (1995) Life cycle analysis of a polyester garment. *Resour Conserv Recycl* 14:233–249
- Steinberger JK, Friot D, Joliet O, Erkmann S (2009) A spatially explicit life cycle inventory of the global textile chain. *Int J Life Cycle Assess* 14:443–455
- Tobler-Rohr MI (2011) Handbook of sustainable textile production, Woodhead Publishing Series in Textiles. Woodhead Publishing Limited, Cambridge
- Todd JA, Curran MA (1999) Streamlined life-cycle assessment: a final report from the SETAC North America Streamlined LCA Workgroup. Society of Environmental Toxicology and Chemistry (SETAC), SETAC Foundation for Environmental Education
- VDMA (2009) Blue competence brochure “Conserving resources—securing savings-potential. The comparison, measuring and labelling of energy-efficient textile machinery”. VDMA, Frankfurt am Main
- Verhulst NHW (2010) Designing a high value application for textile out of non-wearable second hand clothing. M.Sc. Graduation Report IO1115642, Institutional Repository Delft University of Technology
- Vogtlander JG (2013) Eco-efficient value creation, sustainable design and business strategies. VSSD, Delft
- Vogtlander JG, Bijma A (2000) The virtual pollution prevention costs '99: a single LCA-based indicator for emissions. *Int J Life Cycle Assess* 5(2):113–124
- Vogtlander JG, Brezet HC, Hendriks CF (2001) The virtual ecocosts '99: a single LCA-based indicator for sustainability and the eco-costs/value ratio (EVR) model for economic allocation. *Int J Life Cycle Assess* 6(3):157–166
- Walser T, Demou E, Lang DJ, Hellweg S (2011) Prospective environmental life cycle assessment of nanosilver T-shirts. *Environ Sci Technol* 45(10):4570–4578
- Wever R, Vogtlander J (2012) Eco-efficient value creation: an alternative perspective on packaging and sustainability. *Packag Technol Sci*. doi:10.1002/pts.1978
- Yang Y, Li S (1999) Dyeing behavior of 100 % poly(trimethylene terephthalate) (PTT) textiles. *Text Chem Color Am Dyest Report* 1(3):50–54
- Yeh KN, Smith BF (1983) An investigation of selected dye carriers used in commercial dyeing of hydrophobic fibres. Environmental Protection Agency, USA

Publication 2: Carbon sequestration in LCA P.2

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Carbon sequestration in LCA, a proposal for a new approach based on the global carbon cycle; cases on wood and on bamboo

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Abstract

Purpose There are many recent proposals in life cycle assessment (LCA) to calculate temporary storage of carbon in bio-based products. However, there is still no consensus on how to deal with the issue. The main questions are: how do these proposals relate to each other, to what extent are they in line with the classical LCA method (as defined in ISO 14044) and the global mass balances as proposed by the IPCC, and is there really a need to introduce a discounting system for delayed CO₂ emissions?

Methods This paper starts with an analysis of the widely applied specification of PAS 2050 and the ILCD Handbook, both specifying the credit for carbon sequestration as ‘optional’ in LCA. From this analysis, it is concluded that these optional calculations give rather different results compared to the baseline LCA method. Since these optional calculations are not fully in line with the global carbon mass balances, a new calculation method is proposed. To validate the new method, two cases (one on wood and one bamboo products) are given. These cases show the practical application and the consequences of the new approach. Finally, the main issue is evaluated and discussed: is it a realistic approach to allocate less damage to the same emission, when it is released later in time?

Results and discussion This paper proposes a new approach based on the global carbon cycle and land-use change, translated to the level of individual products in LCA. It is argued that only a global *growth* of forest area and a global *growth* of application of wood in the building industry contribute to extra carbon sequestration, which might be allocated as a credit to the *total market* of wood products in LCA. This

approach is different from approaches where temporary storage of carbon in trees is directly allocated to a product itself. **Conclusions** In the proposed approach, there seems to be no need for a discounting system of delayed CO₂ emissions. The advantage of wood and wood-based products can be described in terms of land-use change on a global scale in combination with a credit for heat recovery at the end-of-life (if applicable).

Keywords Bamboo · Carbon sequestration · Carbon storage · LCA · Wood

1 Introduction

In the period 2006–2009, after a long debate on how to calculate biogenic CO₂ in life cycle assessment (LCA), it was decided by the majority of scientists and practitioners that the best approach in LCA is *not* to calculate biogenic CO₂. The basic idea was, and still is, that biogenic CO₂, once captured and stored by trees and other plants, will re-enter the atmosphere sooner or later after the use phase of the product. Hence, in computer programs like Simapro which use the Ecoinvent database (Hischier et al. 2010), biogenic CO₂ was removed from the lists of emissions of the Intergovernmental Panel on Climate Change (IPCC) Global Warming Potential (GWP) midpoint indicators, and consequently from other leading indicator systems like CML-2 and ReCiPe (CO₂ emissions due to land transformation, however, are still counted in these systems). The new ISO 14067 on carbon footprint calculations based on the same logic (Section 6.3.9.2 of the standard, Note 1).

In the last few years, however, there is a feeling in the wood industry and in the industry of other bio-based products, that a credit should be given to bio-based renewable products, which is related to the temporary storage of carbon

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in these products (Brandao and Levasseur 2011; Brandao et al. 2013).

Two important parties reacted on the political will to incorporate carbon sequestration in LCA as an option: the team of the International Reference Life Cycle Data System (ILCD) Handbook (EC-JRC 2010) and the team of the Publicly Available Specification (PAS) 2050:2011 (BSI 2011). In both systems, it is possible to give a credit to temporary CO₂ storage by discounting delayed emissions. Both systems define the credit as optional¹ by the following statements:

- PAS 2050, Section 5.5.1: *‘Note 5. The use of a weighting factor to assess delayed emissions is no longer a requirement of this PAS. However, for entities wishing to undertake such assessment, provision is made in 6.4.9.3.2 and Annex E’.*
- ILCD Handbook, Section 7.4.3.7.3: *‘..i.e., per default, temporary carbon storage and the equivalent delayed emissions and delayed reuse/recycling/recovery within the first 100 years from the time of the study shall not be considered quantitatively’.*

Both systems restrict the calculations on CO₂ sequestration to the 100-year period after the manufacturing of the product (i.e., the 100-year assessment period). In the ILCD Handbook, the 100-year limit is argued to be in line with the decision of LCA scientists and practitioners to keep short- and long-term emissions (from leaching) separate in the LCA calculations (Hischier et al. 2010). The discussion on short- and long-term emissions has many issues (Hischier et al. 2010), but the main argument is summarised in (EC-JRC 2010), regarding the delayed emissions from landfills: *‘...will the inventory of landfills—if the emissions are modelled for e.g., 100,000 years—easily dominate the entire LCA results. This is important to know, but needs a separate interpretation. At the same time, does this issue illustrate one weakness of LCA: LCIA methods usually do not account for thresholds, but aggregate all emissions over time. Hence, even if the concentrations in the waste deposit leachate after 1,000 years might be below any eco-toxic effect, the total amount of these emissions over tenths of thousands of years will be summed up and be considered the same way as the same amount emitted at much higher concentrations over a few years’.* However, this argument for leaching does not hold for CO₂; CO₂ has no toxicity threshold, and the 100-year assessment maximum for carbon sequestration is not only applied to ‘slow’ low level emissions but as well as to pulse (peak) emissions.

¹ The new ISO 14067 specifies that the calculation has to be done ‘without the effect of timing’; however, the effect of timing may be included in a separate report (section 6.3.8)

Another argument to use the 100-year cut-off period is the fact that the GWP midpoint weighting system of IPCC applies a time horizon as well. The 100-year time horizon is the most used in practice, since it was chosen as a basis for the Kyoto protocol. It should be realised that this was a political decision to balance the short term effect of CH₄ and the long-term effect of chlorofluorocarbons. The 100-year time horizon is a rather arbitrary choice (Kendall 2012).

However, there is no scientific reason to confuse the two sequential steps of the baseline LCA calculation, being the life cycle inventory (LCI), and the system to arrive at a single indicator in life cycle impact assessment (LCIA). The classical LCI is a relative straightforward calculation of mass and energy flows: the timing of emissions is not considered, and flows in the LCI are not discounted. Single indicator systems in LCIA, however, are complex and per definition, subjective, and have many time-related issues, sometimes with a long-time horizon, sometimes with a short one.

This paper will deal with the following issues:

- How do the optional calculations of PAS 2050 and the ILCD handbook relate to each other, and how do they relate to the global carbon mass balance as proposed by IPCC? (Section 2)
- To what extent is carbon sequestration dealt with in the baseline LCA method (as defined in ISO 14044)? (Section 3)
- What is the relevance of the global carbon mass balances from the IPCC for LCA? What is the new in the proposed system of this paper? (Section 4)

The consequences of the proposed calculation method are shown in a case on wood products (Section 5) and a case on bamboo products (Section 6). The conclusions and discussion can be found in Section 7 and 8. In these two last sections, the issue of the need for a discounting system for delayed CO₂ emissions is dealt with.

2 The credit for carbon sequestration in relation with the ‘delayed CO₂ pulse’

This section gives a summary of the background of the IPCC calculations on global warming (‘radiative forcing’ caused by CO₂), which is a rather complex issue, however, necessary to understand the idea of the delayed CO₂ pulse. This delayed CO₂ pulse is the basis for the ‘optional’ calculation on carbon sequestration as given in PAS 2050 and the ILCD handbook. Readers who want more information on the issue of radiative forcing are referred to the literature references given in the text.

The 100-year cut-off (‘time horizon’), as mentioned in the previous section, has a fundamental impact on the calculation of the credit for carbon sequestration. This is depicted in

Fig. 1. In this figure the so called Lashof calculation (Fearnside et al. 2000; Clift and Brandão 2008) is given for the decay of a CO₂ pulse in the atmosphere, where the IPCC 2007 formula on the decay of CO₂ has been applied (Solomon et al. 2007) as follows:

$$\begin{aligned} \text{Decay} = & 0.217 + 0.259 \times \text{EXP}\left(-T/172.9\right) + 0.338 \\ & \times \text{EXP}\left(-T/18.51\right) + 0.186 \\ & \times \text{EXP}\left(-T/1.186\right) \end{aligned}$$

where T = time in years after the pulse

Figure 1 shows the effect of applying a time horizon in the calculation. When the CO₂ emission pulse is delayed with the carbon storage time (in the example 50 years), the shaded area will shift out of the time horizon of 100 years; this is the calculation credit which results from the time shift of the emission. The reality, however, is that the CO₂ is still there, so ‘omission’ would be a better word than ‘credit’.

The credit of a delayed-pulse emission as a function of time is given in Fig. 2. It is the result of the Lashof calculation in combination with the 100-year time horizon. The ILCD handbook and PAS 2050:2011 propose a linear approximation (where PAS follows the Lashof calculation for the first 25 years).

The result for both systems (for delay periods more than 25 years) is the same as a linear discounting system would have with a 1 % per year discount rate.

There is, however, no consensus at all on the credit system of Fig. 2, so there is need for further development (Brandao and Levasseur 2011; Brandao et al. 2013).

The Dynamic Life Cycle Assessment approach (Levasseur et al. 2010; Levasseur et al. 2013) seems to be one of the

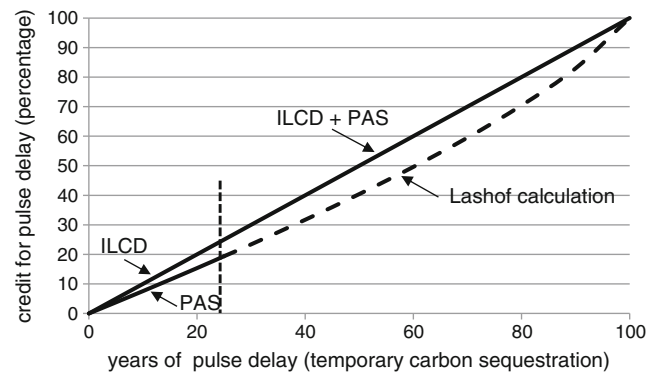


Fig. 2 The credit for a delayed CO₂ pulse in PAS 2050, the ILCD manual, and according to the Lashof calculation of Fig. 1

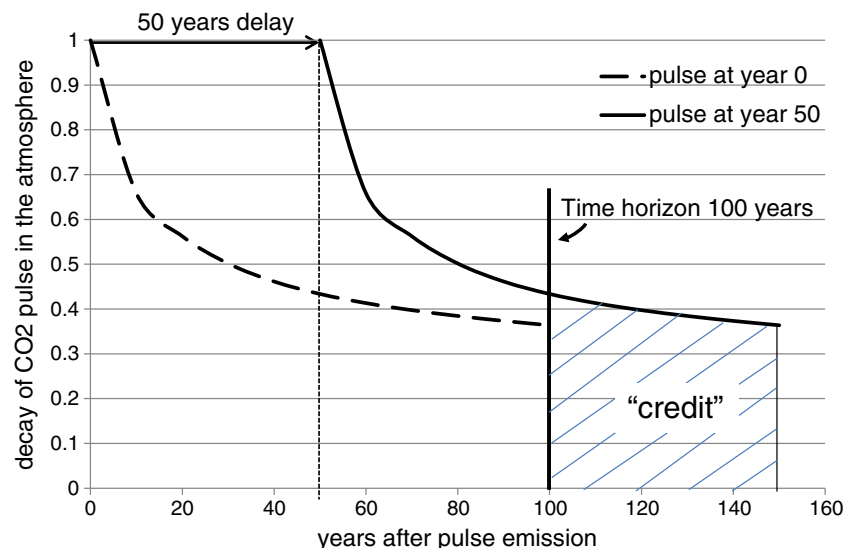
scientific answers on the aforementioned arbitrary credit problem: it has no specific time horizon. This system is based on an integrated radiative forcing calculation of a series of emissions over time. The disadvantage of this calculation system is, however, that the result of the calculation depends heavily on the sequence of pulse emissions in the given scenario. An example on the LCA of a wooden chair shows that there is a remarkable difference (300 %) between two scenarios:

- (1) The tree for the wood is planted 70 years *before* the chair is made
- (2) A new tree is planted at the moment (*after*) a tree is cut for the wood of the chair

The difference of the two scenarios is the period of carbon sequestration by the tree: in year minus 70 until year 0, or in year 1 until year 71.

The interesting aspect of the sequence issue of the Dynamic Life Cycle Assessment approach is that the dilemma of the sequence vanishes when the calculation is made for a manufacturer of wooden chairs: when the manufacturer

Fig. 1 Residence time of CO₂ in the atmosphere and the resulting credit of a delayed pulse as a consequence of the 100-year criterion, according to the Lashof calculation



makes several chairs per year over several decades, the problem can be modelled as a steady-state mass flow calculation. The forest is then regarded as steady state as well: continuously, a small part of the trees is cut and replanted, the major part consists of growing trees, and a small part is ready to be cut. The same steady state applies then to the end-of-life: the combustion of chairs (with or without heat recovery) or the landfill of chairs is regarded as a continuous flow. With this reasoning, we are back to the original way of calculation in LCI. The remaining issue then is how to cope with the aspect of land-use change (afforestation, reforestation, better forest management and deforestation) when the steady-state flow increases or decreases. This will be dealt with in Sections 5 and 6.

A remarkable issue in the approach of the ILCD Handbook and PAS 2050:2011 is that the credit of delaying emissions is to be applied to bio-based products as well as fossil-based products like polymers ('the atmosphere does not differentiate between the two types of CO₂'). Since many polymers have a higher ratio of 'kg carbon'/kg product', many polymers seem to benefit more from the credit for delayed emissions. Neither the industry nor the politicians seem to be aware of this issue (Brandao and Levasseur 2011; Brandao et al. 2013).

The advantage of carbon sequestration in wood and other bio-based products (over oil based polymers) in the baseline LCA, however, is not related to the delayed emissions, but is related to the end-of-life scenario, as explained in Section 3.

3 The relevance of carbon sequestration at product level in LCI

Although the biogenic CO₂ is not counted in LCIA, it is required to keep track of the biogenic CO₂ in LCI (EC-JRC 2010), see Fig. 3.

Biogenic CO₂ is first taken out of the air in the forest (plantation), and then released back to the atmosphere at the end-of-life. So, biogenic CO₂ is recycled, sooner or later in time. When a wood product or a bamboo product, however, is burnt with energy recovery at end-of life (e.g., in an electrical power plant), the total system of Fig. 3 generates an output flow (e.g., electricity). This heat or electricity replaces energy production from other sources, including

fossil fuels. In other words: the use of fossil fuels and the related emissions is avoided, which results in a reduction of the potential global warming effect. In LCI calculations, this can be modelled as a system credit: the production of heat or electricity from wood waste has a negative carbon footprint. This is the so called substitution approach in consequential modelling, see Section 14.5 of the ILCD Handbook (EC-JRC 2010).

The conclusion of this section is that there is no system credit for the biogenic CO₂ cycle, unless the wood (or any other bio-product) is burnt for electricity and/or heat, and unless the trees are replanted. A better efficiency of the production of electricity results in a higher credit.

4 A general description of carbon sequestration at global level

The effects of carbon sequestration can be understood when studying it at a global system level (Vogtlander 2010). On a global scale, CO₂ is stored in forests (and other vegetation), in the ocean, and in products (e.g., buildings and furniture). The details of carbon mass balances are very complex; however, an understanding of the basics of the proposed LCA method in this paper requires a system approach which starts from the highest possible aggregation level (the so called "Tier 1" and "Tier 2" approach of the IPCC). In this approach, we look at vast forest areas (e.g., Scandinavia, the Baltic countries, European Russia, Siberia, Canada, New Zealand). At this aggregation level, there is a continuous rotation of the forests. The local time-dependent carbon sequestration effects caused by harvesting are levelled out within the region since only a small proportion of the trees are harvested each year. Figure 4 is a simplified schematic overview of the highest aggregation level of the global carbon cycle.

The issue is that the anthropogenic CO₂ emissions on a global scale can be characterised by three main flows:

- Carbon emissions per year caused by burning of fossil fuels: 6.4 Gt/year (Solomon et al. 2007)
- Carbon emissions per year caused by deforestation in tropical and sub-tropical areas (Africa, Central America, South America, South and Southeast Asia): 1.93 Gt/year (FAO 2010)

Fig. 3 The life cycle of biogenic CO₂

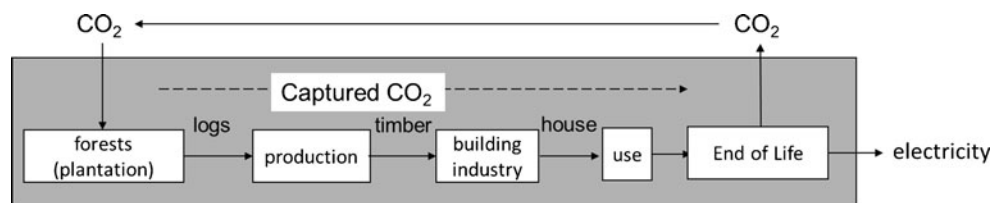
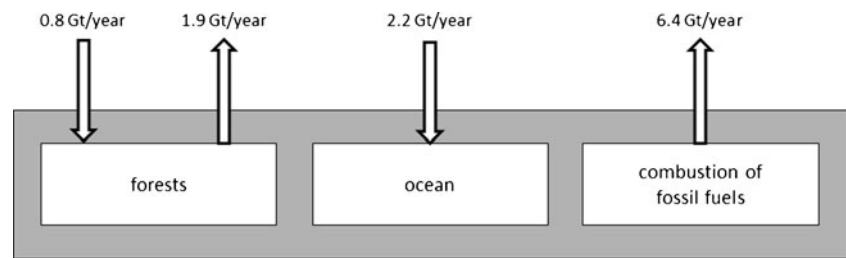


Fig. 4 Global anthropogenic fluxes of CO₂ (Gt/year) over the period 2000–2010



- Carbon sequestration per year by re-growth of forests on the Northern Hemisphere (Europe, North America, China): 0.85 Gt/year (FAO 2010)

It can be concluded that the global carbon cycle can significantly be improved in the short term by the following changes (1) burn less fossil fuels, (2) stop deforestation, (3) intensify the use of forest on the Northern Hemisphere by better management and wood production in plantations, (4) afforestation (plant trees on soils that have not supported forests in the recent past), (5) increase application of wood in durable (construction) products, such as buildings.

However, it is far too simple to claim that application of wood in design and construction will lead to carbon sequestration and therefore it will counteract global warming. It depends on the origin of wood and the growth of the wood markets. One should realise that, if there is *no change* in the area of forests and *no change* in the volume of wood in buildings there is *no change* in sequestered carbon on a global level and hence *no effect* on carbon emissions. This means that only when *more* carbon is being stored in forests (either by area expansion with an increase of net carbon storage on that land, or by increased productivity in existing forests by improved management), and when the *total volume* of wood in buildings is *increasing*, there will be extra carbon sequestration.

In boreal and temperate regions such as in Europe and North America, the forest area is increasing steadily for several decades due to afforestation and reforestation (see Fig. 5), which results to increased carbon storage over the last decennia (see Fig. 6).

Figure 6 shows that carbon storage in tropical areas is decreasing. The demand for tropical hardwood is higher than the supply from plantations (only 35–40% of Forest Stewardship Council (FSC)-wood is from plantations). This leads to deforestation, resulting in carbon emissions caused by less carbon sequestration. This mechanism is depicted in Fig. 7.

The conclusion in regard to the production side of wood is:

- Extra demand of boreal and temperate softwood from Europe and North America leads to a better forest management and an increase in forest area therefore more sequestered carbon (Fig. 5)

- (Extra) demand of tropical hardwood leads to a decrease in forest area, therefore less sequestered carbon (Fig. 7)

Extra demand of bamboo in China has an effect on carbon sequestration which is similar to that of European and North American wood: it leads to a better forest management and an increase in bamboo forest area (Lou Y et al. 2010).

The carbon sequestration in wood in houses and offices is slowly rising on a global scale (because of increasing population), which is as such positive in terms of extra carbon sequestration. This volume of carbon sequestration, however, is low in comparison with the volume of standing trees in the forests: less than 30 % of the carbon above the ground (= less than 24 % of the carbon above plus under the ground) ends up in housing, which is explained in Section 5, steps 1 and 4.

The conclusion is that carbon sequestration is enhanced when more boreal or temperate softwood from Europe and North America and/or bamboo is applied in housing, since more carbon is sequestered in the forests as well as in the houses. On the contrary, the application of tropical hardwood is damaging carbon sequestration, since the decrease of carbon in the tropical forests is more than the increase of carbon in the wood products.

Another key issue of the global mass balance is that carbon sequestration is not increasing per house which is built, but per extra house that is built above the number of houses that are required to replace discarded, old, houses. This is an important consequence of the global mass balance,

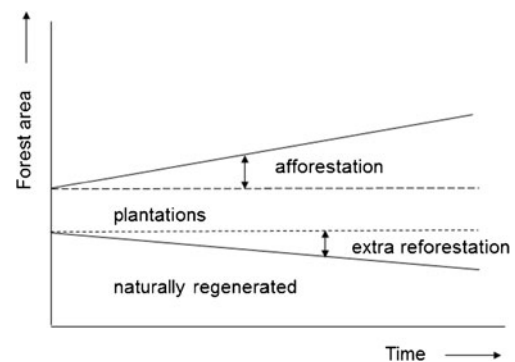


Fig. 5 Higher demand of boreal and temperate softwood from Europe and North America leads to more carbon sequestration because of afforestation (extra forests) and reforestation (converting naturally regenerated forests to plantations and better forest management)

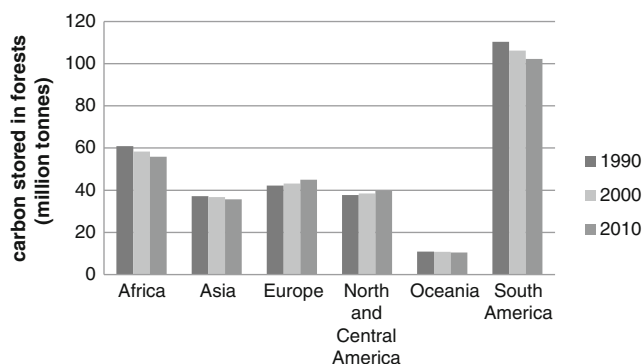


Fig. 6 Trends in carbon storage in forests from 1990–2010 (Source: FAO 2010)

which is often overlooked by LCA practitioners when they study carbon sequestration at product level in the LCI phase of the assessment.

In LCA, the aforementioned global aspect of carbon sequestration in forests is defined in terms of land-use change. The remaining question then is: how to allocate the positive or negative effect of carbon sequestration in forests on global scale to the wood or bamboo at product level?

In this paper, we propose an *allocation of the extra global carbon sequestration in forests to the total global production of wood products*. Such an allocation method is applied since it is not realistic to assign the extra trees to specific wooden products. This allocation method is different from the way the optional calculations are specified in PAS 2050 and the ILCD manual.

The way the proposed allocation method of this paper is done in practice is explained in Step 3 of the examples in Sections 5 and 6.

5 Example 1: calculation of carbon sequestration caused by land-use change for European softwood

The aim of the calculation in this section is to illustrate how the proposed method is done in practice, and to validate the

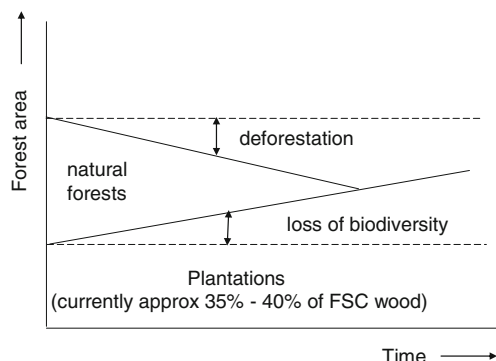


Fig. 7 Higher demand of tropical hardwood leads to deforestation and less carbon sequestration

method as such (by checking the impact on the output of each calculation step).

The scope of the calculation is the carbon sequestration in boreal softwood from cradle-to-grave, excluding emissions from forest management equipment, product manufacturing, transport, and end-of-life operations (a so called “streamlined” LCA approach). The geographical system boundary is Europe, as defined in (FAO 2010)

The calculation of carbon sequestration caused by land-use change for wood is done in five steps:

- (1) The calculation of the relationship (ratio) of carbon stored in forests and carbon stored in end-products (planed timber); this first step is in compliance with baseline LCA
- (2) The calculation of a land-use change correction factor (to cope with the fact that there was another type of biomass before the area was changed to forests); this step is in compliance with the IPCC standards
- (3) The calculation of the *extra* stored carbon in forests (see Fig. 5), because of *growth of wood production*, and its allocation to the end-products (i.e., planed timber); this step, and the way of allocation, is proposed in this paper by the authors
- (4) The calculation of the *extra* stored carbon in houses and offices, because of *growth of the volume*; this step is in compliance with PAS 2050 and the ILCD handbook optional credit
- (5) The final calculation of the total result of carbon sequestration: the multiplication of the results of steps 1, 2, 3, plus the result of step 4.

Step 1 Calculation of the carbon ratio

It is important to realise that 1 kg of a wooden end-product relates to many kilograms of wood in the forests, which has been calculated according to the baseline LCA procedure, applying Ecoinvent data:

- 1-kg biomass, dry matter (d.m.) in standing trees, is equivalent to 0.65 kg of logs (Werner et al. 2007)
- 0.65-kg d.m. of logs, is equivalent to $0.65 \times 0.585 = 0.38$ kg of sawn timber (Werner et al. 2007)
- 0.38-kg d.m. sawn timber is equivalent to $0.38 \times 0.87 = 0.33$ kg of planed timber (Werner et al. 2007)
- 1-kg d.m. biomass in standing trees is equivalent to 1.25-kg d.m. total biomass, since the root/shoot ratio is 0.25 (Aalde 2006)
- 1-kg d.m. of planed timber originates from $1.25/0.33 = 3.79$ -kg d.m. biomass in the forests
- The carbon content is 0.5-kg C per 1-kg wood (Aalde et al. 2006; Verchot et al. 2006)

- Therefore, 1-kg d.m. planed timber, is equivalent to the storage of $3.79 \times 0.5 = 1.9$ -kg carbon in the forest
The result of step 1 is that 1-kg d.m. planed timber is related to $1.9 \times 3.67 = 6.97$ kg CO₂ storage in the forest.

Step 2 Calculation of the land-use change correction factor

The next step in the calculation is related with the land-use change: before the afforestation, the land had also stored biomass. So the ‘Tier 2 Gain–Loss Method’ (Verchot et al. 2006) of the IPCC has to be applied (it must be mentioned that this method is not described in the ILCD Handbook, Annex B (EC-JRC 2010); however, it is fully in line with the requirement of section 7.4.4.1 page 234). The essence of this gain–loss method is a comparison of the steady state *before* and *after* the of land-use change. For European boreal softwood, we assume that there was grass before the afforestation since the boreal areas are hardly used for agriculture (agriculture is concentrated in warmer areas).

The ‘total above-ground and below-ground non-woody biomass’ for grass is 7.5-t d.m./ha (it ranges from 6.5 to 8.5), with a carbon content of 47 % (Verchot et al. 2006).

The biomass of softwood forests, is assumed at 120-t d.m./ha (Aalde et al. 2006) for the above-ground biomass, with a root/shoot ratio of 0.25 and a carbon content of 50 %.

The land-use change correction factor for afforestation is therefore:

$$\frac{\{(120 \times 1.25 \times 0.50) - (7.5 \times 0.47)\}}{(120 \times 1.25 \times 0.50)} = \mathbf{0.953}$$

For reforestation, the situation is different when the land-use change is from ‘naturally generated’ forests to plantations. Data on biomass in the Global Forest Resources Assessment 2010 of the Food and Agriculture Organisation of the United Nations (FAO 2010) and Aalde et al. (2006) suggest that the biomass in plantations might be about twice the biomass in naturally generated forests. The land-use change correction factor is 0.5 for such cases, based on the total wood production, and 1.0 based on the *extra* wood production.

Step 3 Calculation of *extra* stored carbon in forests and its allocation

In Section 4, it was explained that only the *extra* biomass in forests makes a differences in terms of less CO₂ in the atmosphere. The total biomass in the European forests was 88,516 million tonnes in 2005

and 90,602 million tonnes in 2010 (FAO 2010). So there was a growth in biomass of 2,086 tonnes, or 2.36 % in 5 years. This is about 0.47 % per year.

For the calculation in step 5, the authors propose to base the yearly growth of the total biomass in forests on the expected average growth of European timber production of 2.3 % (UNECE 2005). There are two arguments to take the market growth of European timber production: (1) The growth of biomass may not always be in balance with the timber production, since the stock of biomass is very high (the turnover of stock is very low). (2) The measurement of biomass in forests is quite problematic, and therefore less accurate than the market growth of timber production (FAO 2010).

The related growth of yearly extra carbon storage in the forests is to be allocated to the total yearly production of wooden products.

Step 4 Calculation of the *extra* stored carbon in houses and offices

The extra carbon sequestration in houses and offices is related to the planed timber minus ‘application losses’, which we estimate at 10 %. This results in $0.9 \times 0.5 \times 3.67 = 1.65$ kg CO₂ storage in the houses per 1-kg d.m. planed wood. The *extra* storage is related to the market growth given in step 3. This extra carbon sequestration is:

$1.65 \times 0.023 = 0.038$ kg CO₂ per kilogram dry matter planed timber

Step 5 Calculation of the total result

The effect on carbon sequestration caused by land-use change can be calculated now as follows:

$$\text{carbon sequestration} = 6.97 \times 0.953 \times 0.023 + 0.038 = \mathbf{0.19 \text{ kg CO}_2 \text{ per kilogram diameter planed timber}}$$

6 Example 2: calculation of carbon sequestration caused by land-use change for Chinese bamboo (*Phyllostachys pubescens*)

The aim of the calculation in this section is to illustrate how the proposed method is applied in practice in the case of bamboo products, and to validate the method as such (by checking the differences compared to European softwood in each calculation step).

The scope of the calculation is the calculation on carbon sequestration in Chinese bamboo from cradle-to-grave, excluding emissions from forest management, product manufacturing, transport, and end-of-life operations (a so called ‘streamlined’ LCA approach). The geographical system boundary is China, as defined in (FAO 2010)

The calculation is made for *Phyllostachys pubescens* (density 700 kg/m³, length up to 15 m, diameter on the ground 10–12 cm, wall thickness 9 mm), also called Moso, from the Anji region, the province of Zhejiang, China. It is processed to planed bamboo products like plywood and strand woven bamboo (SWB) in Huangzhou, the province of Zhejiang. SWB is a relative new industrial bamboo product with a high Janka hardness (12,500 N) and density (1,080 kg/m³), made from compressed bamboo strips plus resin. For LCI data of the production processes, see (Vogl  nder et al. 2010; Van der Lugt 2009).

The calculation for Chinese bamboo is done via the same steps as given in Section 5.

Step 1 Calculation of the carbon ratio.

One kilogram of a bamboo end-product relates to many kilograms of wood in the bamboo plantation:

- 1-kg biomass, d.m. above the ground in the bamboo plantation, is equivalent to 0.42 kg of bamboo in the end-product (Van der Lugt et al. 2009)
- 0.42-kg d.m. of bamboo, is used in 0.44-kg d.m. plywood (the resin content is 5 % of the weight of plywood) and in 0.546-kg d.m. SWB (the resin content is 23 % of the weight of SWB) (Van der Lugt et al. 2009)
- 1-kg d.m. biomass above the ground in the bamboo plantation is equivalent to 3.1-kg d.m. biomass above + below the ground, since bamboo has a vast root system²
- 1-kg d.m. of bamboo plywood originates from $3.1/0.44=7.05$ -kg d.m. biomass in the bamboo plantation, and 1-kg d.m. of SWB originates from $3.1/0.546=5.7$ -kg d.m. biomass in the bamboo plantation
- The carbon content is 0.5 kg C per 1-kg bamboo (Aalde et al. 2006; Verchot et al. 2006)
- Therefore, 1-kg d.m. bamboo plywood is equivalent to the storage of $7.05 \times 0.5 = 3.5$ kg carbon in the plantation, and 1-kg d.m. SWB is equivalent to the storage of $5.7 \times 0.5 = 2.85$ kg carbon in the plantation

The result of step 1:

- 1-kg d.m. bamboo plywood is related to $3.5 \times 3.67 = 12.85$ kg CO₂ storage in the plantation
- 1-kg d.m. SWB is related to $2.85 \times 3.67 = 10.5$ kg CO₂ storage in the plantation

² Besides the trunks, branches, and shrub, there is CO₂ stored below ground in the soil and roots of a plantation. Zhou and Jiang (2004) found that, for a medium intensity managed Moso bamboo plantation in Lin'an, Zhejiang province, the distribution of biomass above ground versus below ground is 32.2 and 68.8 %, respectively.

Step 2 Calculation of the land-use change correction factor

It is assumed that the additional permanent plantations are established on grassland and do not come at the expense of natural tree forests. This is a plausible assumption as a large portion of the Moso bamboo resources comes from the industrialised provinces around Shanghai (Zhejiang, Anhui, Jiangxi). Furthermore, this assumption fits well in the current policy for afforestation and natural forest protection of the Chinese Government controlled by the Chinese State Forestry. More information on this issue can be found at (CSF 2013).

Similar to the calculation of this step in Section 5, the Tier 2 Gain–Loss Method (Verchot et al. 2006) of the IPCC has to be applied. The ‘Total above-ground and below-ground non-woody biomass’ is 7.5-t d.m./ha (it ranges from 6.5 to 8.5) with a carbon content of 47 % (Verchot et al. 2006).

The biomass of bamboo plantations is $35.8 \times 3.1 = 111$ t d.m./ha for biomass above + below the ground (Van der Lugt 2009; Zhou and Jiang 2004), and a carbon content of 50 %.

The land-use change correction factor for afforestation is therefore:

$$\{(111 \times 0.50) - (7.5 \times 0.47)\} / (111 \times 0.50) = \mathbf{0.936}$$

Much of the extra Chinese bamboo production in the past comes from better management (Lou Y et al. 2010) of existing bamboo forests. In such a case the land-use change correction factor is 1 for the *extra* bamboo production.

Step 3 Calculation of *extra* stored carbon in forests and its allocation

The Seventh Chinese National Forestry Inventory provides data on the growth of bamboo plantations in China. In the period 2004–2008, bamboo plantations have grown from 4.84 to 5.38 million hectares, or 11.2 % in 5 years or 2.24 % per year. The growth of tree forest area in China is at a similar level (11.7 %).

It does make sense, however, to base the future yearly growth of the total biomass in bamboo forests on the average growth of Chinese timber production,³ which is expected to be at least 5 % for the coming decades, given the high GDP of the Chinese economy. The related growth of yearly extra carbon storage in the

³ Here is a similar argumentation as in footnote 2 for European wood. It must be mentioned here that this growth does not require extra agricultural land. Much of the bamboo production in the past comes from better forest management (Lou et al. 2010). Moreover, bamboo is planted in areas where farming is not feasible, e.g., at slopes for erosion prevention, and for rehabilitating land (Kuehl Y et al. 2011)

plantation is to be allocated to the total yearly production of bamboo products.

Step 4 Calculation of the *extra* stored carbon in houses and offices

The extra carbon sequestration in houses and offices is related to the bamboo products minus application losses, which we estimate at 10 %. Taking into account the resin content in the end-product (5 % for plywood and 23 % for SWB), this results in:

- $0.95 \times 0.9 \times 0.5 \times 3.67 = 1.57$ kg biogenic CO₂ storage in the houses per 1-kg d.m. bamboo plywood. The *extra* storage, related to the market growth in step 3, results in the *extra* carbon sequestration of $1.57 \times 0.05 = 0.0785$ kg CO₂ per kilogram dry matter bamboo plywood.
- $0.77 \times 0.9 \times 0.5 \times 3.67 = 1.27$ kg biogenic CO₂ storage in the houses per 1-kg d.m. SWB. The *extra* storage, related to the market growth in step 3, results in the *extra* carbon sequestration of $1.27 \times 0.05 = 0.0635$ kg CO₂ per kilogram dry matter SWB.

Step 5 Calculation of the total result

The effect on carbon sequestration caused by land-use change can be calculated now as follows:

- Carbon sequestration = $12.85 \times 0.936 \times 0.05 + 0.0785 =$ **0.68 kg CO₂ per kilogram dry matter bamboo plywood**
- Carbon sequestration = $10.50 \times 0.936 \times 0.05 + 0.0635 =$ **0.55 kg CO₂ per kilogram dry matter SWB**

7 Discussion

The discussion on how to deal with the carbon sequestration in LCA reveals that some important issues in the LCA methodology are still not resolved (Finkbeiner 2009). This paper shows that methodological choices highly influence the outcome of the LCA calculations.

Table 1 shows the data on the baseline LCA method of Section 3 (the first four columns), compared to the land-use

change approach of Section 4 (the last column). Ecoinvent LCIs are used for softwood, and the Idemat 2012 LCI is used for bamboo plywood (Vogtländer et al. 2010; Van der Lugt et al. 2009). Idemat is a database which is used at the Delft University of Technology, additional to Ecoinvent.

From Table 1, it can be concluded that the credit for the carbon sequestration caused by the land-use change, as presented in this paper, is relevant in comparison to the emissions caused by the production. The calculation for production is made for the default method of the ILCD handbook: biogenic CO₂ has not been taken into account, so the production data in the Table is for fossil CO₂ only. The credit for combustion with heat recovery has been calculated for two different levels of efficiency: an efficiency of a modern coal fired electrical power plant of 45 % (IEA 2007), and an efficiency of a modern municipal waste incinerator of 24.75 %. The ‘avoided fossil fuels’ are calculated for the grid average energy mix of the Ecoinvent ‘electricity, medium voltage, production Union for the Coordination of the Transmission of Electricity (UCTE), at grid/UCTE S’ LCI.

Table 2 provides some additional data with regard to the issue of linear discounting of a delayed CO₂ pulse in 100 years (a 100-year time horizon). The issue here is whether or not discounting brings additional information which cannot be missed.

The discounting of a delayed CO₂ pulse results in a credit in LCA (column 1 of Table 2), but reduces the credits for combustion with heat recovery (column 2 and 3 of Table 2 compared to column 3 and 4 of Table 1), so the overall effect of discounting is limited. Note also that the effect of discounting in Table 2 is an overestimation of the benefit in reality since there is still a considerable amount of CO₂ in the atmosphere after the 100-year cut-off criterion of in the Lashof calculation (see Fig. 1, Section 2).

Given the fact that the result of the discounting is limited, and that it gives an overestimation of the resulting credit, the discounting system of the delayed CO₂ pulse does not make sense in LCA, since it does not fulfil the precautionary principle (which should be applied in LCA).

Furthermore, the traditional LCA accounting system has the advantage that the approach on the level of one product is

Table 1 Traditional LCA data on European softwood and Chinese bamboo

All data in kg CO ₂ equivalent, IPCC 2007 GWP 100a			Combustion	Municipal	Land-use
	Production kg CO ₂ e/m ³	Production kg CO ₂ e/kg	Power plant kg CO ₂ e/kg	Waste incin kg CO ₂ e/kg	change this paper kg CO ₂ e/kg
Sawn timber, softwood, planed, air dried, at plant/RER S (d.m. 80 %)	85	0.21	−1.08	−0.59	−0.15
Sawn timber, softwood, planed, kiln dried, at plant/RER S (d.m. 90 %)	104	0.26	−1.21	−0.67	−0.17
Idemat2012 Plywood Bamboo (including transport to Europe, d.m. 90 %)	811	1.16	−1.13	−0.62	−0.61

Table 2 The effect of a discounted CO₂ pulse at the end-of-life (after 50 years, linear discounting 1 % per year) on LCA data of European softwood and Chinese bamboo

All data in kg CO ₂ equivalent, IPCC 2007 GWP 100a	Optional Carbon sequestration ILCD 50 years kg CO ₂ e/kg	Heat recovery In power plant ILCD after 50 years kgCO ₂ e/kg	Heat recovery In munic waste incin ILCD after 50 years kgCO ₂ e/kg
Sawn timber, softwood, planed, air dried, at plant/RER S (d.m. 80 %)	−0.734	−0.540	−0.295
Sawn timber, softwood, planed, kiln dried, at plant/RER S (d.m. 90 %)	−0.826	−0.605	−0.335
Idemat2012 Plywood Bamboo (d.m. 90, 5 % resin)	−0.785	−0.565	−0.310

in line with the approach of a continuous flow of products (of the same type), which makes it robust for a wide range of scenarios (from a local to a global level). The traditional LCA is also less vulnerable for different assumptions on the decay of wood in landfill: in wet regions the decay is fast, in dry regions slow, which has a big impact in calculations with a time horizon.

An important issue is how to implement the proposed method of this paper in practice. What are the implications for LCA practitioners and to what level of detail land-use change should be addressed?

A practical aspect is the availability of data. For the 12 global regions in (FAO 2010) enough data are available to make a Tier 2 calculation on the *average* forests in that region. At the level of specific types of timber in the global trade (e.g., spruce, scots pine, radiata pine, etc.), however, data are not readily available. The most practical approach to resolve that problem might be that FAO includes the required information in their FAOSTAT database (at the level of the 233 countries), an initiative that should be done in close cooperation with the developers of ILCD, USLCI and Ecoinvent.

The accuracy of the Tier 2 calculations on specific types of timber in the global trade cannot be high since wood is a natural product with a rather high variation of the main growth characteristics of the trees. It is important, however, that data become available: data with low accuracy is better than no data at all.

With regard to the accuracy of calculations on carbon sequestration, it is important to realise that the carbon footprint is only one of the environmental indicators related to land-use change. Two other important issues with regard to land-use change are:

- The albedo effect of deforestation and reforestation in boreal areas. The change in albedo (surface reflection) in areas with snow has an effect on global warming which is of the same magnitude as the effect of carbon sequestration in forests (Cherubini et al. 2012).
- The reduction of biodiversity caused by deforestation of tropical rain forests. Reduction of biodiversity of natural forests is one of the main issues in the debate on tropical

hardwood, making a difference between illegal logging, reduced impact logging, FSC-certified logging and logging from plantations. This is one of the main arguments to use an indicator system that takes this important aspect into account (as a midpoint), like the ReCiPe system or the system of the eco-costs (Vogtländer et al. 2001; Vogtländer et al. 2004).

8 Conclusions

The conclusions with regard to the issue of carbon sequestration are as follows:

- The afforestation and reforestation related to a growing application of boreal softwood, wood from temperate regions, and bamboo products have a significant contribution to carbon sequestration on a global level
- An even bigger contribution is the reduction of fossil CO₂ emissions by combustion with heat recovery (production of electricity) of the wood and bamboo products at the end-of-life

The conclusions with regard to the LCA methodology are as follows:

- Proper modelling of the end-of-life stage results in a considerable credit for wooden products in the case of combustion with heat recovery. There is no reason to deviate from this ‘default’ method in the ILCD Handbook and PAS 2050:2011.
- The ‘optional’ method in the ILCD manual and PAS 2050:2011 (i.e., discounting of the delayed CO₂ emissions) results in an overestimation of the benefits of temporary fixation of biogenic CO₂. This optional method does not fulfil the precautionary principle, and should therefore be avoided in LCA
- It is advised to reconsider the calculation procedure to deal with carbon sequestration in wood (and other bio-based products), as described in the ILCD Handbook Section 7.4.3.7.3, 7.4.4.1, and Section 13, and bring it in line with Section 4 and the examples in Section 5 of this paper

- Land transformation data of general LCI databases should be applied with great care, since they cannot simply be applied to single products (as explained in Section 4).

The way that carbon sequestration in wood products is dealt with in LCA, needs further refinement. In the proposed approach there seems to be no need for a discounting system of delayed CO₂ emissions. The advantage of wood and wood-based products can be described in terms of land-use change on a global scale in combination with a credit for heat recovery at the end-of-life (if applicable). However, the availability of data on transformation of land is limited (on the level of specific types of timber), so systematic collection of reliable data is required.

References

- Aalde H, Gonzalez P, Gytarsky M, Krug T, Kurz WA, Ogle S, Raison J, Schoene D, Ravindranath NH, Elhassan NG, Heath LS, Higuchi N, Kainja S, Matsumoto M, Sánchez MJS, Somogyi Z (2006) IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4, Chapter 4 Forest Land. Available at www.ipcc.ch. Accessed 6 Feb 2013
- Brandao M, Levasseur A (2011) Assessing temporary carbon storage in life cycle assessment and carbon foot printing: outcomes of an expert workshop JRC 63225. Publications Office of the European Union, Luxembourg
- Brandao M, Levasseur A, Kirschbaum MUF, Weidema BP, Cowie AL, Vedel Jørgensen S, Hauschild MZ, Pennington DW, Chomkamsri K (2013) Key issues and options in accounting for carbon sequestration and temporary storage in life cycle assessment and carbon footprinting. *Int J Life Cycle Assess* 18(1):230–240
- BSI, British Standards Institution (2011) PAS 2050: 2011 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. BSI, London
- Cherubini F, Bright RM, Strømman AH (2012) Site-specific global warming potentials of biogenic CO₂ for bioenergy: contributions from carbon fluxes and albedo dynamics. *Environ Res Lett* 7:045902. doi:10.1088/1748-9326/7/4/045902
- Clift R, Brandão M (2008) Carbon storage and timing of emissions. University of Surrey. Centre for Environmental Strategy Working Paper Number 02/08. ISSN: 1464–8083, Guildford
- CSF (2013) website Chinese State Forestry, <http://english.forestry.gov.cn/web/index.do>. Accessed 6 Feb 2013
- European Commission–Joint Research Centre and Institute for Environment and Sustainability (2010) International reference life cycle data system (ILCD) handbook—general guide for life cycle assessment—detailed guidance. Publications Office of the European Union, Luxembourg
- FAO (2010) Global forests resources assessment, Forestry Paper 163. Food and Agriculture Organisation of the United Nations, FAO. Available at www.fao.org/forestry. Accessed 6 Feb 2013
- Fearnside PM, Lashof DA, Moura-Costa P (2000) Accounting for time in mitigating global warming through land-use change and forestry. *Mitig Adapt Strateg Glob Chang* 5:239–270
- Finkbeiner M (2009) Carbon footprinting—opportunities and threats. *Int J Life Cycle Assess* 14(2):91–94
- Hischier R, Weidema B, Althaus H-J, Bauer C, Doka G, Dones R, Frischknecht R, Hellweg S, Humbert S, Jungbluth N, Köllner T, Loerincik Y, Margni M, Nemecek T (2010) Implementation of life cycle impact assessment methods. Ecoinvent report No. 3, v2.2. Swiss Centre for Life Cycle Inventories, Dübendorf
- IEA (2007) Biomass for Power Generation and CHP. Available at <https://www.iea.org/techno/essentials3.pdf>. Accessed 6 Feb 2013
- Kendall A (2012) Time-adjusted global warming potentials for LCA and carbon footprints. *Int J Life Cycle Assess* 17:1042–1049
- Kuehl Y, Henley G, Lou Y (2011) The climate change challenge and bamboo: mitigation and adaptation. IMBAR, Beijing. Available at <http://www.inbar.int/publications/?category=1&sortby=title&dlpage=4>. Accessed 6 Feb 2013
- Levasseur A, Lesage P, Margni M, Deschenes L, Samson R (2010) Considering time in LCA: Dynamic LCA and its application to global warming impact assessments. *Environ Sci Technol* 44(8):3169–3174
- Levasseur A, Lesage P, Margni M, Samson R (2013) Biogenic carbon and temporary storage addressed with dynamic life cycle assessment. *J Ind Ecol* 17(1):117–128
- Lou Y, Li Y, Buckingham K, Henley G, Zhou G (2010) Bamboo and Climate Change Mitigation. IMBAR, Beijing. Available at <http://www.inbar.int/publications/?category=2>. Accessed 6 Feb 2013
- Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (2007) IPCC Fourth Assessment Report: Climate Change (AR4), The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge. Available at www.ipcc.ch. Accessed 6 Feb 2013
- UNECE, United Nation Economic Commission for Europe (2005) European Forest Sector Outlook Study 1960–2000–2020, Geneva Timber and Forest Study Paper 20. Available at <http://www.unecce.org/forests-welcome/publications.html>. Accessed 6 Feb 2013
- Van der Lugt P, Vogtlander J, Brezet J (2009) Bamboo a sustainable solution for Western Europe. VSSD, Delft
- Verhot L, Krug T, Lasco RD, Ogle S, Raison J, Yue Li, Martino DL, McConkey BG, Smith P (2006) IPCC guidelines for national greenhouse gas inventories. Volume 4, Chapter 6 Grass Land. Available at www.ipcc.ch. Accessed 6 Feb 2013.
- Vogtlander J, Brezet J, Hendriks CF (2001) The Virtual Eco-costs '99, a single LCA-based indicator for sustainability and the Eco-costs/Value Ratio (EVR) model for economic allocation. *Int J Life Cycle Assess* 6(3):157–166
- Vogtlander JG, Lindeijer E, Witte J-PM, Hendriks C (2004) Characterizing the change of land-use based on Flora: application for EIA and LCA. *J Clean Prod* 12:47–57
- Vogtlander J, Van der Lugt P, Brezet J (2010) The sustainability of bamboo products for local and Western European applications LCAs and land-use. *J Clean Prod* 18:1260–1269
- Vogtlander J (2010) A practical guide to LCA for students, designers and business managers, cradle-to-grave and cradle-to-cradle. VSSD, Delft
- Werner F, Althaus H-J, Künniger T, Richter K, Jungbluth N (2007) Life cycle inventories of wood as fuel and construction material. Ecoinvent Report No. 9. Swiss Centre for Life Cycle Inventories, Dübendorf
- Zhou GM, Jiang PK (2004) Density, storage and spatial distribution of carbon in *Phyllostachys pubescens* forest. *Sci Silvae Sin* 6:20–24 (in Chinese with English summary)

Publication 3: Monetisation of external socio-economic costs P.3

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Monetisation of external socio-economic costs of industrial production: A Social-LCA-based case of clothing production

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Abstract

Purpose

The purpose of this study is to benchmark production processes and production chains of clothing products, by means of S-LCA. In this paper we present the s-eco-costs method for monetisation of external socio-economic burden for workers. The method is applied to six cases of standard textile production chains: the supply chains of a cotton T-shirt and a pair of jeans, produced in either the USA-Europe or China/India-Bangladesh.

Methods

The s-eco-costs are the marginal prevention costs to reach a sustainable level (Performance Reference Point, PRP) and comprise the monetary compensation beyond the PRP to account for unacceptable exploitation of workers.

At this moment the s-eco-costs include five sub-indicators, proposed as a base-line for the social issue in S-LCA:

- Fair Wage Deficit (based on migration statistics and data on minimum wages; the subcategory-indicator as well as the end-score are expressed in euro)

- Child Labour (forced labour, not able to attend school; subcategory-indicator: DALY; end-score: euro)
- Extreme Poverty (based on World Bank absolute poverty line and FAO price index; subcategory-indicator: DALY; end-score: euro)
- Excessive Working Hours (forced labour, involuntary; subcategory-indicator: DALY; end-score: euro)
- Occupational Safety and Health (based on statistics of ILO; subcategory-indicator: DALY; end-score: euro)

Results and discussion

The s-eco-costs have been calculated for cotton T-shirts and pairs of jeans for three garment production chains: USA-Europe (Western 'W'); India-Bangladesh (Asian 'A'); China/India-Bangladesh (Asian Best Practice 'ABP'), revealing the hotspots in these chains, and enabling benchmarking. The total results for the s-eco-costs of T-shirts are: W = € 0.05; A = € 1.46 and ABP = € 0.33 euro. The results for the jeans are: W = € 0.38; A = € 12.56 and ABP = € 2.67 euro. The most important hotspots are in the cotton fields in India and the garment production phase in Bangladesh.

Conclusions

The s-eco-costs system provides a lot of transparency in the complex issue of social sustainability in production chains in general, and in the garment production case under study. Hotspots can be determined and alternative production routes can be benchmarked.

The authors hope that the proposed system will inspire others in the field of S-LCA to proceed with the development of quantitative indicator systems.

Keywords:

s-eco-costs · textiles · extreme poverty · child labour · fair wage · China - India - Bangladesh

Highlights:

- S-eco-costs is proposed as a S-LCA-method for benchmarking textile supply chains.
- The study presents 6 cases of standard textile production chains (T-shirts; jeans).
- The hotspots are the Indian cotton fields and the Bangladesh garment factories.

1. Introduction

The textile and apparel industry is associated with several sustainability problems. Anticipating on a prospective growth of this sector (according to Lenzing (2015) and Choudhury (2014) the world fibre production is rising by about 3% per annum), it is important to determine the environmental and social impacts of clothing products. Well-founded analyses can inform decision makers to outline the transition towards a more sustainable fashion industry. Stakeholders in this perspective comprise fashion designers and companies, manufacturers of textiles and clothing products, non-governmental organisations (NGOs), consumers and authorities. In this paper we specifically address the producers and the consumers of textile and apparel, but other, even non-textile related readers, can also find valuable information concerning method development of Life Cycle Sustainability Assessment (LCSA; Kloeppfer, 2008).

Life Cycle Assessment (LCA; ISO 2006a; ISO 2006b) is a systematic scientific method for a quantified benchmark at different levels, depending on the defined system (product - or process level, cradle-to-gate; - grave or - cradle). This method allows for a comparison between, among others, different materials or product alternatives, as well as for comparing complete production chains or industries. In a previous publication (Van der Velden et al., 2014) we describe an environmental LCA of textiles produced according to the Best Practice in Europe, including a comparison of textiles made out of different fibre materials. Likewise, LCA has often been used to determine the best available technique (BAT) for a specific process, for example by Nieminen et al. (2007) and Terinte et al. (2014) on textile wet processing and by Shen et al. (2010) on the production of man-made cellulose fibres. The latest study includes as well a geographical comparison between production locations (of the fibre materials), which is also addressed by Steinberger (2009) for specific garments (T-shirt and jacket). All aforementioned references and more (Roos et al. 2015a; Yuan et al. 2013; Zhang et al. 2015) describe the environmental aspects of life cycle assessment (E-LCA), but do not include any social issues.

According to the UNEP/SETAC (2009, p.49), social life cycle assessment (S-LCA) can be used to assess – among other categories - the stakeholder category ‘worker’ and the unacceptable exploitation of workers in the textile chain. In this manuscript we present a qualitative method to do so; which is in line with the UNEP/SETAC guidelines for LSCA (UNEP/SETAC, 2011). Without doubt the holistic S-LCA approach, as described by for example the OECD (2010) and Helliwell et al. (2013), reaches wider than assessment of the un-

sustainability of the production systems only, and therefore the authors confirm that the proposed method in this paper addresses by no means the actual well-being of people in general.

The published papers on S-LCA are still rather limited (compared to E-LCA), and they all show that there still are many problems in conducting S-LCA. The development of S-LCA is still in its infancy (Mattioda et al., 2015) and consensus of opinion on which indicators (Lehmann et al., 2013; Bocoum et al., 2015) and LCI data (Benoît Norris, 2014) should be used, has not been reached yet.

There are some good examples of hotspot analyses on roses (Franze and Ciroth, 2011), on laptops (Ekener-Petersen and Finnveden, 2012), on palm oil (Manik et al, 2013), and on fertilizer (Martinez-Blanco et al, 2014) which used the data of the Social Hotspot DataBase (Benoît Norris, 2014). The key problem in all these examples is that data should be available for at least the most relevant specific manufacturing locations in the production chain, and that these specific data are hard to get (Jorgenson, 2013). Benoît Norris (2014) even argues that comparison (LCA benchmarking) is not possible because of the sensitivity of these specific data. One recent paper on building materials proposes a well-structured panel weighting system for a single score in S-LCA (Hosseinijou et al, 2013), however, it is rather complex for a quick assessment in practice, and a full integration with E-LCA in LCSA (UNEP/SETAC, 2011) to one single score, as required in engineering and design practice, seems still not possible.

S-LCA benchmarking is required to take the right decisions in the purchasing processes in the apparel industry. It is as well an indispensable tool to boost continuous improvement at the production sites of the suppliers, which should be pursued by at least all members of the Sustainable Apparel Coalition (SAC, 2015). For sustainable consumer behaviour it is essential that “you know what you buy”. So S-LCA should be made understandable and doable for these purposes. That motivated us to develop the method of Section 2.

The purpose of this paper is to introduce the s-eco-costs method and to give an example of the application of this method by means of mapping out the textile supply chain. The method has been developed at first instance for the stakeholder category “worker” as an extension of the eco-costs method (a method of impact assessment originally developed for E-LCA, Vogtländer et al., 2001).

The purpose of the s-eco-costs method in S-LCA is to benchmark production processes and production chains. An analysis of the s-eco-costs (S-LCA) should be accompanied by an analysis of the eco-costs (E-LCA, see Fig.

1 in Section 2.2) to enable a well-balanced decision process with regard to improvement of the total production chain.

As a validation of the method, we demonstrate how the s-eco-costs can be applied to enable a comparison between different specific textile production chains, where we focus on the social aspects related to the workers in that sector. In developing countries social issues of the textile supply chain arise during cotton production and the subsequent processing steps; and in the final garment production. Many references (Mariani, 2013; ILO, 2014; Kelly, 2014) indicate these garment life cycle phases as the social hotspots, where the unacceptable exploitation of workers takes place. All other negative social effects in the subsequent phases and in background systems are expected to be of less importance.

We present six cases of standard textile production chains, namely the cases of a cotton T-shirt and a pair of jeans, produced in USA-Europe, India-Bangladesh, or China-India-Bangladesh. See Section 3.2.

The s-eco-costs method is designed to be applied for hotspot analyses in order to diminish antisocial situations in the production chain. In combination with the method of the eco-costs it also may be used to support the decision making process of choosing and/or improving the most sustainable option (route) during the life cycle of a product, where social issues of workers play a role next to environmental issues.

In the following sections of this paper we will describe the method of the s-eco-costs: first the introduction and the goal and scope of the method (section 2.1 and 2.2), then the calculation structure of the subcategory-indicators (section 2.3), and finally the calculation of the end-scores (section 2.4).

In Section 3 we apply the method to 11 textile producing countries (section 3.1), and 2 different products (a T-shirt and a jeans) from 3 different production chains (section 3.2).

The Discussion (section 4) deals with four issues: a. to what extent is it allowed to apply s-eco-costs; b. the issue whether or not the multipliers are too high or too low; c. how the eco-costs of garment production relate to the s-eco-costs of garment production; d. how the s-eco-costs garment production relate to the actual market price of garments.

The Conclusions (section 5) summarize the results of the analysis of the textile chains, and includes suggestions for further development of quantitative S-LCA studies.

2. An indicator system for S-LCA: the s-eco-costs

2.1 Introduction to the s-eco-costs

The s-eco-costs method is in line with the Guidelines for S-LCA of Products (UNEP/SETAC, 2009) and follows the methodological framework as presented in the UNEP/SETAC Life Cycle Initiative document Towards a Life Cycle Sustainability Assessment (UNEP/SETAC, 2011). It comprises the subcategories of Fair Wage Deficit, Child Labour, Extreme Poverty, Excessive Working Hours, and Occupational Safety and Health..

The s-eco-costs of the Fair Wage Deficit are the marginal prevention costs to reach a sustainable level, which is the Performance Reference Point (PRP) (UNEP/SETAC, 2009; Parent et al., 2010; UNEP/SETAC, 2011; Benoît Norris, 2014). The distance to the PRP for the other subcategories can be considered as costs of compensation to account for unacceptable exploitation of workers.

2.2 Goal and scope of the s-eco-costs method

The goal of the s-eco-costs method is:

1. to focus on the unsustainable and appalling working conditions in the supply chain (suitable for cradle-to-cradle analyses as well)
2. to quantify product related social topics (child labour, extreme low wages, unsafe work places, et cetera)
3. to quantify results of S-LCA in a way that the unsustainability of a product can be communicated to designers, business managers, and the public
4. to provide transparency in the calculations, based on general statistical data (World Bank, ILO, Eurostat, etc.) and specific data which can easily be measured at the production sites
5. to be complementary to (i.e. can be combined with) the eco-costs system for (E)-LCA, i.e. having monetized indicators

A consequence of point 1 is that the method is not meant for internal assessment of highly developed companies in the Western World, where issues as ‘permanent education’, ‘work-life balance’ and ‘job satisfaction’ are significant issues (Round Table for Product Social Metrics, 2014). We think that the appalling situations (mostly further upstream and located in the Middle and Far East and in Africa, but sometimes in illegal production

facilities in the Western World as well) in the supply chain should be handled with priority. Business managers have a responsibility here to improve their supply chains, and buyers have the responsibility to pay perhaps a bit higher price when the product is made in a more sustainable way. They both need metrics to be informed properly, and to base their decisions on.

Another consequence of point 1 is that s-eco-costs only deal with the stakeholder group of ‘workers’ as far as working conditions are unacceptable. S-eco-costs are external costs, not integrated in the price of the product, and are based on the distance to the sustainable target (the Performance Reference Point, PRP) of an impact category.

Fig. 1 presents the overview of the structure of the eco-costs and the s-eco-costs. The background of the eco-costs method was introduced in this journal by Vogtländer et al. (2002) and the s-eco-costs are explained in the following Sections 2.3 and 2.4.

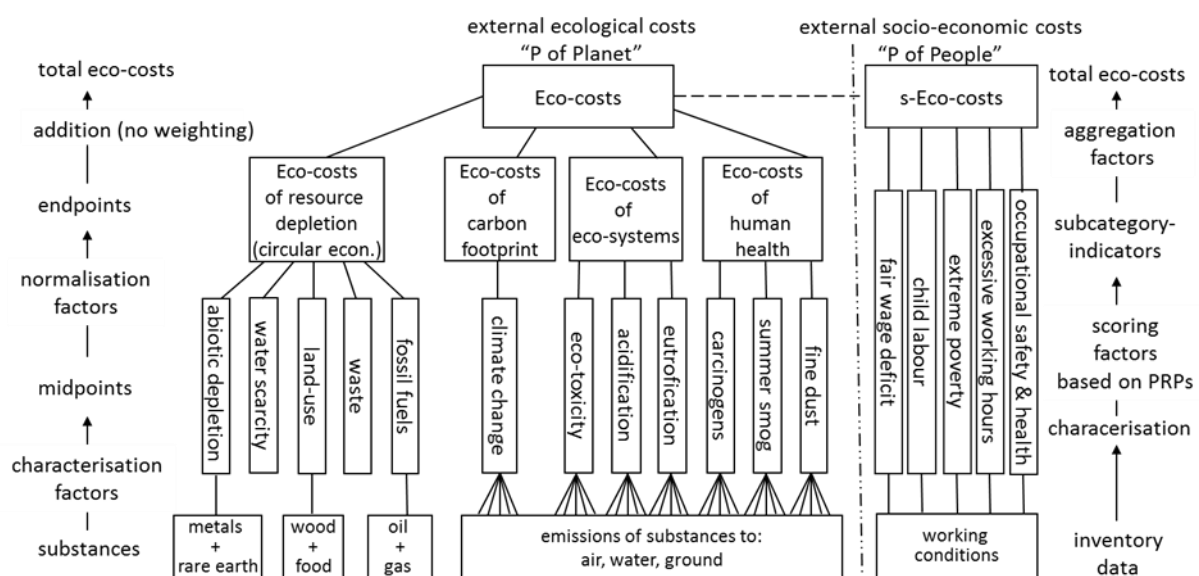


Fig. 1 Structure of the eco-costs and the s-eco-costs

2.3 The subcategory-indicators

2.3.1 General approach

In line with the five issues of the goal of the method, there are five requirements for subcategory-indicators:

- the issue must be specific, relevant and easy to understand

- b. data must be available at the level of countries (to be able to benchmark between countries, and to have an average practice to compare with within a country)
- c. data must be relatively easy to measure at the level of specific manufacturing plants
- d. it must be applicable to products (the S-LCA has to be made on the level of a product, since its results must be communicated to designers, business managers and consumers)
- e. it must be possible to translate a 'subcategory-indicator' (a specific indicator for a specific 'subcategory') to an 'end-score' (a single indicator for the stakeholder category 'worker').

All eight subcategories for the category 'worker' - Freedom of Association and Collective Bargaining, Child Labour, Fair Salary, Working Hours, Forced Labour, Equal opportunities/Discrimination, Health and Safety, Social Benefits/Social Security (UNEP/SETAC, 2009) - have been analysed with regard to the five aforementioned requirements. This results in the five subcategories of s-eco-costs:

1. Fair Wage Deficit
2. Child Labour
3. Extreme Poverty (caused by wages which are too low to feed the family)
4. Excessive Working Hours, involuntary (forced labour in excess of 48 hours per week)
5. Occupational Safety and Health (OSH)

The following subcategories cannot be applied in the s-eco-costs:

- Equal Opportunities/Discrimination (since it is hard to measure)
- Freedom of Association and Collective Bargaining (since it is a complex issue in many developing countries, and hard to establish)
- Social Benefits/Social Security (since it is hardly implemented in developing countries; when it is present at a specific factory, it should be counted as part of the salary as far as that it can be monetized)

Some scientists emphasise the importance of a restricted level of inequality of salaries in a company, e.g. less than a factor 23.8 (Croes and Vermeulen, 2016a). Although the issue is important, it cannot be measured in most of the companies in the developing world (the income of the boss, often the owner, is generally not known). The same applies to the issue of corruption (UNEP/SETAC, 2011): such an issue is hard to measure and quantify.

The s-eco-costs of a product are based on the salaries per working hour of shop floor employees, and the required time to make a product. Both data must be measured at the factory and based on the actual situation.

To benchmark unsustainable situations on the level of a country, statistical data have to be used.

In this paper we apply the following general conversion factors to define the metrics of the s-eco-costs on a country level:

- Calculations on the fair wage deficit are done on the basis of Purchasing Power Parity (because the normal exchange rates of currencies would give the wrong picture). For data see the website of the OECD (OECD, 2015). The conversion factor in the s-eco-costs metrics is: 1 Int \$ PPP = 0.83 euro.
- To calculate the salaries per working hour in a country outside the European Union, the general norm of the ILO, 49 weeks of 48 hours, is applied, minus 14 public holidays. This results in 2240 hours per year, 280 days of 8 hours per year, 6 days of 8 hours per week, for 46.7 weeks (note that work in overtime is calculated separately).
- To calculate the salaries per working hour within the European Union, the following norms have been used: 1840 hours per year, 230 days of 8 hours per day, 5 days of 8 hours per week for 46 weeks (see Table 6 in Annex A for an overview of the norms for working hours).

In the following Sections 3.2.2 through 3.2.6, the five subcategory-indicators are defined for each subcategory.

Per subcategory of the s-eco-costs, the choices which have been made are described step by step:

- first, the issue of the subcategory (i.e. a description of the unsustainable problem)
- then, the PRP (the minimum target level) is proposed for the subcategory, to enable the distance-to-target calculation
- finally, the characterisation function (equivalent to the characterisation factors in E-LCA) is determined, which is the key to the distance-to-target subcategory-indicator score (Int \$ PPP / hour, or DALY / year) for the specific working condition in a production facility

The factors which are required to create the end-score (euro / hour) are proposed in Section 3.3.

2.3.2 Fair Wage Deficit subcategory-indicator

The issue. The difference of wages between the rich countries and in the developing countries is not only unfair, but is unsustainable as well. It is causing an increasing pressure of migration of shop floor workers to the rich countries, as confirmed by Dustmann et al. (2003). There is no other solution for this problem than to bring all wages to a fair level.

The PRP. The performance reference point in the s-eco-costs system is the point where the issue is solved (this is similar to the approach of marginal prevention costs in the eco-costs system). To find the PRP, we analysed the migration within Europe, which has been studied extensively (e.g. by OECD, 2012; Dustmann et al., 2003 and Holland et al., 2011). Dustmann et al. suggest that there is virtually no migration when the income per capita in the poor country is higher than 2/3 of that of the rich country, and that migration starts below 1/2. This assumption is more or less confirmed by the data of Holland et al. (2011). Since the s-eco-costs system requires a PRP on shop floor wages, we calculated the relationship between migration and the ratio of the minimum wages in the poor and the rich countries (the ‘relative minimum wage’) within the European Union. See Fig. 2. This figure shows that migration increases with low wages, and that migration stops at a ratio of approximately 50%. The dotted curve in Fig.2 is a curve-fit ($y = 0.1 x^{-0.396}$, $R^2 = 0.7593$), which crosses the 50% line at 0.037% emigration per year, which might be regarded as a sustainable migration flow. The data in Fig.2 are after the accession of the countries, so migration between countries without physical and legal boundaries.

It is obvious that Fig. 2 cannot be applied to predict the size of migration in general, since migration in general is affected by many other factors as well, such as well-being (with the many aspects as described in (OECD, 2011; Helliwell et al., 2013) and in the Inequality-adjusted Human Development Index); barriers for migration (physical and legal); cultural differences and extreme local conditions (e.g. wars, starvation), but the size of migration is not the subject of this paper. The subject of this paper is what is being described as ‘economic migration’ in relation with the role of production companies in this respect.

The minimum wage in the rich countries of the EU member states is around 1775 Int \$ PPP per month, plus or minus 15%, year 2014 (Wageindicator Foundation 2015; OECD 2015), so the PRP for Fair Wage is $0.50 \times 1775 = 888$ Int \$ PPP per month ($888 \times 12 / 1840 = 5.79$ Int \$ PPP per hour).

The characterisation function. The characterisation function of the Fair Wage Deficit is determined by the distance to the target (the PRP), see Fig. 2. In formula:

$$(1) \quad I_{FWD} = PRP_{FWD} - S_{hour} \quad \text{if } PRP_{FWD} > S_{hour}$$

$$(2) \quad I_{FWD} = 0 \quad \text{if } PRP_{FWD} \leq S_{hour}$$

where:

I_{FWD} = Fair Wage Deficit indicator (Int \$ PPP/hr)

PRP_{FWD} = 5.79 (Int \$ PPP/hr)

S_{hour} = actual salary per hour (Int \$ PPP/hr)

Example: when a worker has an actual salary of 2.50 Int \$ PPP/hr, the Fair Wage Deficit indicator is 5.79-2.50 = 3.29 Int \$ PPP/hr

When the actual production site is not yet known, the minimum wage for countries might be taken, which can be found at (Trading Economics, 2015), and (Wageindicator Foundation, 2015).

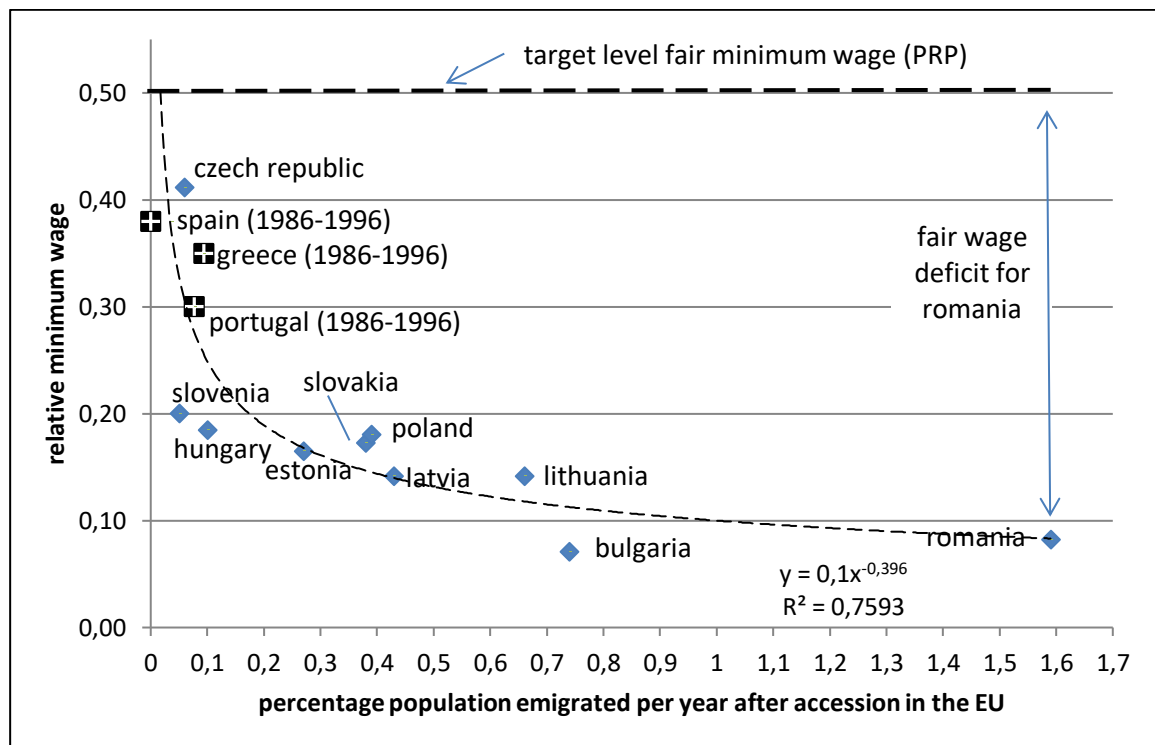


Fig. 2 Percentage of population migrated after the accession in the EU as a function of relative minimum wage

2.3.3 Child Labour subcategory-indicator

The issue. The definition of child labour is rather complex, but it is related to the fact that children are deprived of the opportunity to attend school (ILO, 2015). The age is not part of the definition, since it depends on culture and situation. The ILO convention on child labour takes 15 years as a basis. Worldwide, 58.6% of the child labour is in agriculture, 7.2% in industry, 25.4% in services (e.g. hotels, restaurants, retail, social personal services), and 6.9% domestic work (ILO, 2013). Child labour is in a way related to the issue of extreme poverty (the parents are forced to ask their children to work), but it should be eradicated anyway where it obstructs education, since education is the way out of poverty.

The PRP. The performance reference point (the target) in the s-eco-costs system for the industry is set to zero hours/year, as a consequence of the fact that it should be eradicated. The fact that these children cannot attend school, and appalling circumstances of their lives, makes that 1 year of Child Labour is set equal to 1 ‘lost life year’. To quantify such a lost life year we have chosen to apply the DALY (disability-adjusted life year), which has been developed by the WHO to classify the burden of a disease from mortality and morbidity (WHO, 2004). It is also used in the ReCiPe indicator system for E-LCA. In the s-eco-costs system 2240 hours/year of child labour equals to 1 DALY as a default value.

It is obvious that there are many forms of child labour, from severe forms of slavery related to hazardous work to less severe forms of helping parents at home. It is also obvious that the age of the child plays a role as well.

However, we could not find any quantified classification system, since it is still to be developed (ILO, 2015).

The consequence for S-LCA is that the default value of 1 year child labour is 1 DALY cannot be differentiated yet: the S-LCA practitioner has to decide whether or not to set this default value higher (when children are traumatised) or lower than 1 (in case of no injuries and no mental traumas). WHO (2004) may give some guidance. The reason that we propose 1 DALY as default is that child labour should be eradicated anyway, so any default value is better than skipping the subject “because there is no scientific measure to differentiate”.

The PRP for agriculture, services and domestic work is a bit more complicated, since many cultures stimulate children to do some work after school. Therefore the PRP for these sectors is set to 2 hours per day ($2240/8 \times 2 = 560$ hours per year) as an absolute maximum. Above this 2 hours education is likely to suffer, which we regard as not acceptable (see Table 6 in Annex A for an overview of the norms for working hours).

The characterisation function. The characterisation function of child labour is:

$$(3) \quad I_{CLindustry} = H_{CL}/C_{CL}$$

$$(4) \quad I_{\text{CLagriculture}} = (H_{\text{CL}} - 560)/C_{\text{CL}} \quad \text{for } H_{\text{CL}} > 560 \text{ hours per year}$$

$$(5) \quad I_{\text{CLagriculture}} = 0 \quad \text{for } H_{\text{CL}} \leq 560 \text{ hours per year}$$

where:

$I_{\text{CLindustry}}$ = Child Labour indicator in industry (DALY/year)

$I_{\text{CLagriculture}}$ = Child Labour indicator in agriculture, services and domestic (DALY/year)

H_{CL} = working hours per child per year (hr/year)

C_{CL} = DALY conversion factor = 2240 (hr/DALY)

Example: when a child works 1000 hr/year in a factory, the Child Labour indicator is $1000/2240 = 0.45$

DALY/year

2.3.4 Extreme Poverty and slavery subcategory-indicator

The issue. Extreme poverty in the s-eco-costs system is defined by the fact that the wage is not enough to buy enough food in the family, under the assumption that a standard family is man, wife plus 2 children, and that either the man or the wife is employed for 2240 hours per year. Croes and Vermeulen (2016b) give an excellent overview of all variations on this assumption in literature.

Extreme poverty leads to a form of ‘modern slavery’, which can be considered as extreme exploitation of workers: when the wage is near to zero, the worker is caught in a poverty trap (not able to escape the terrible situation, and forced to ask his/her children to work for their own food). When the wage is zero, it is slavery.

The PRP. For a wage of zero (slavery) the indicator is proposed as 1 DALY/year. The reason for this default value, and the deliberations why, is similar to that of child labour (see Section 2.3.3). The PRP, however, is the level where this specific problem is over: the point where there is enough wage for food and other essential things for living. The calculation of the PRP is based on the assumptions of the World Bank: the 1.25 Int \$ PPP (2005) absolute poverty line (the absolute minimum needs for living per person per day), and the assumption that aforementioned standard family is 2.7 people equivalent (the man is 1, the woman is 0.7, and a child is 0.5 person equivalent). Applying the food price index of the FAO for the period 2005 – 2014 (food became factor 1.7 more expensive), we assume 1 worker per family (2240 hours, 280 days per year), which results in the PRP of the Extreme Poverty:

$$1.25 \times 2.7 \times 1.7 \times 365/280 = 7.48 \text{ Int \$ PPP per day, } 2094 \text{ Int \$ PPP per year, } 0.935 \text{ Int \$ PPP per hour.}$$

This PRP is the target in the s-eco-costs system for the Extreme Poverty indicator.

The characterisation function. The characterisation function of Extreme Poverty is:

$$(6) \quad I_{EP} = (PRP_{EP} - W_{year})/C_{EP} \quad \text{if } PRP_{EP} > W_{year}$$

$$(7) \quad I_{EP} = 0 \quad \text{if } PRP_{EP} \leq W_{year}$$

where:

I_{EP} = Extreme Poverty indicator (DALY/year)

PRP_{EP} = 2094 (Int \$ PPP/year)

W_{year} = actual wage per year (Int \$ PPP/year)

C_{EP} = DALY conversion factor = 2094 (Int \$ PPP/DALY)

Example: when the salary of a worker is 1000 Int \$ PPP/year, the Extreme Poverty indicator is $(2094 - 1000)/2094 = 0.49$ DALY/year

Note. Double counting with the Fair Wage Deficit indicator should be avoided, as explained in Fig. 3, Section 3.3.

2.3.5 Excessive Working Hours (forced labour) subcategory-indicator

The issue. This issue is related to the fact that at some production sites workers are forced to work more than 48 hours per week, leading to exhaustion. When this is involuntary, it is to be regarded as a form of modern slavery. It is reported frequently in the Chinese production facilities for electronic equipment (CLW, 2012).

To quantify the Excessive Working Hours we propose the DALY as indicator (as we did in Section 3.2.3 for Child Labour and in Section 3.2.4 for Extreme Poverty), proportional to the number of Excessive Working Hours.

The PRP. The performance reference point (the target) in the s-eco-costs system for extreme working hours is set to zero (as far as the working hours are involuntary).

The characterisation function. The characterisation function of Excessive Working Hours is:

$$(8) \quad I_{EWH} = (H_{EWH} - 2240)/C_{EWH} \quad \text{only for } H_{EWH} > 2240$$

where:

I_{EWH} = Excessive Working Hours indicator (DALY/year)

H_{EWH} = working hours per year (hr/year)

C_{EWH} = DALY conversion factor = 2240 (hr/DALY)

Note. In case of very irregular working times, it is advised to do the calculation on a weekly basis.

Example: when a worker has to work 2500 hr/year, the Excessive Working Hours indicator is $(2500-2240)/2240$
 $= 0.12$ DALY/year

2.3.6 Occupational Safety and Health (OSH) subcategory-indicator

The issue. Legislation in the field of Health and Safety is different from country to country, and the way specific production sites adhere (or not) to the legislation is a matter of local culture, norms and values of the management. So although the indicator is important, the problems are the way the data can be gathered in manufacturing plants and non-disclosure of this data of a company. It is relatively easy to interview workers on their wage and working hours (via asking them when they are not at work), but data on sick leave and injuries they might have had in the past can only be gathered via the management (because they probably do not remember the exact data of sick leaves or injuries of themselves nor of their colleagues). In the textile producing countries it is not so easy to collect this kind of data because the (sometimes corrupt) executives in this sector are often not too open about these issues. To obtain the right LCI data it could help to exert pressure from the downstream companies via purchasing and expediting procedures.

The PRP. The performance reference point (the target) in the s-eco-costs system for work related injuries, illness, and mortality is zero.

On the level of countries, worldwide, data were gathered more than 10 years ago (ILO 2003), and there are many examples - as described by e.g. Berik and Rodgers (2010) and Mariani (2013) - that the situation has not been improved in the textile producing countries since then. The Rana Plaza garment factory collapse in April 2013 killed more than 1100 people and this incident shocked the world and was the occasion for the formulation of the Bangladesh Accord on Fire and Building Safety, which have been signed now by many textile companies. For the OSH indicator we analysed 'work related illness and accidents causing at least 4 days absence' and 'work related mortality' (ILO 2003).

The characterisation function. The characterisation function of OSH is:

$$(9) \quad I_{OSH} = (C_A \times P_A) + (C_M \times P_M)$$

where:

I_{OSH} = OSH Indicator (DALY/yr)

P_A = number of accidents and work related illness causing over 4 days' absence per year/number of workers

P_M = number of work related death per year/number of workers

C_A = average lost life year per case (DALY)

C_M = average lost life year per calamity (DALY) = average life expectancy in a country - age of the worker

Note 1. C_A is rather small: estimate from US data (BLS, 2013) is less than $1/12 = 0,08$ DALY

Note 2. Characterisation factors for countries can be found at www.ecocostsvalue.com tap data

2.4 The end-scores

The goal of the s-eco-costs method is to benchmark products (from cradle-to-gate, from cradle-to-grave, or from cradle-to-cradle). The end-scores must therefore be given 'per hour of processing', and must be monetized, to fulfil requirement number 3 of Section 3.1.

So the last step in the s-eco-costs system is to monetize the DALY. In the medical science, the DALY is used to make comparisons in terms of prevention costs. It was developed by the WHO to assess the costs efficacy of medical cure in the developing countries (where financial resources are scarce). Because of the progress in medical science, efficacy of medical care in the rich countries becomes an issue as well (we could give more medical treatment than our society can afford). For pharmaceutical products a maximum price of 40.000 to 50.000 euro per DALY is accepted in Europe, however, higher prices are suggested for medical cure in hospitals. In the USA the price of kidney dialysis ("the dialysis standard") is proposed as the maximum price for 1 DALY (Grosse, 2008) (King et al. 2005), being 82.000 US \$ in 2009 (NIH, 2012). Although the DALY cannot be used as tool for medical decision making on the level of the individual patient (Cleemput et al., 2011), it is often used for general guidance for higher level policy decisions. RVZ (2006) proposes 80.000 euro per DALY in Europe. One of the basic principles for the eco-costs, as well as for the s-eco-costs, is that a life in a poor country has the same value as a life in a developed country, so we apply 80.000 euro per DALY.

This results in the following conversion factors in the s-eco-costs method:

- | | | |
|---------------------|-----------------------------|-------------------------|
| - Fair Wage Deficit | 1 I_{FWD} (Int \$ PPP/hr) | = 0.83 (euro/hr) |
| - Child Labour | 1 I_{CL} (DALY/year) | = 80.000/2240 (euro/hr) |

- Extreme Poverty $1 I_{EP}$ (DALY/year) = 80.000/2240 (euro/hr)
- Excessive Working Hours $1 I_{EWH}$ (DALY/year) = 80.000/2240 (euro/hr)
- OSH $1 I_{OSH}$ (DALY/year) = 80.000/2240 (euro/hr)

Fig. 3 shows the characterisation lines for extreme poverty and fair wage deficit. This figure demonstrates that - to avoid double counting - the fair wage deficit should not be accounted for when the wage is lower than 0.823 Int \$ PPP per hour. In that case only the s-eco-costs of extreme poverty should be taken into account (and the s-eco-costs of fair wage must be left out).

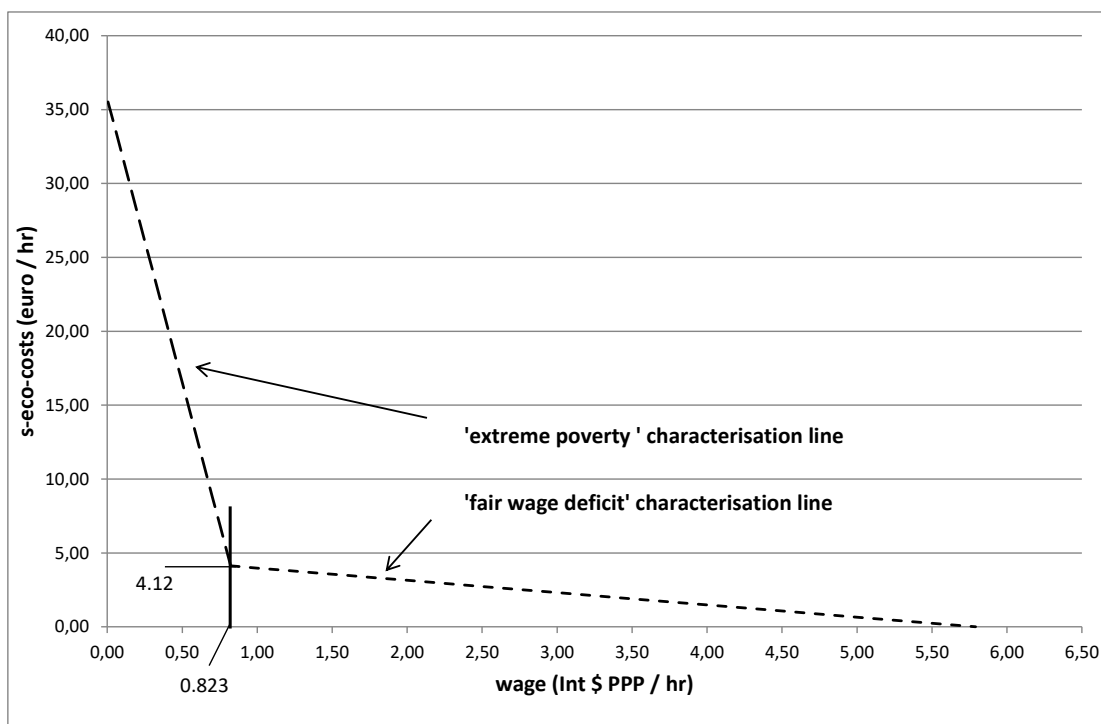


Fig. 3 The s-eco-costs as a function of the wage

The total s-eco-costs can be calculated as following:

$$(10) \quad \text{Total s-eco-costs} = 0.83 \times I_{FWD} + (I_{CL} + I_{EWH} + I_{OSH}) \times 80000/2240 \text{ euro for } I_{FWD} > 0.823$$

$$(11) \quad \text{Total s-eco-costs} = (I_{CL} + I_{EP} + I_{EWH} + I_{OSH}) \times 80000/2240 \text{ euro for } I_{FWD} < 0.823$$

3. Results

3.1 S-eco-costs on a country level

To show some examples of the application of the s-eco-costs method for the textiles industry on a country level, Table 1 provides the s-eco-costs per hour for some key producing countries of textile products (e.g. China, Bangladesh and Vietnam).

The outcomes in the table are based on the general minimum wages at a specific moment in time. The s-eco-costs for the Bangladesh industry in general are much higher than the s-eco-cost for the Bangladesh garment industry, due to a higher legal minimum wage for garment workers in that country.

For future calculations the data must be adjusted to the situation under study (minimum wages constantly fluctuate, especially in rapidly advancing developing countries).

The specific LCI data for Child Labour and Extreme Working Hours must be acquired on the level of a specific production chain, since ILO data on child labour and extreme working hours are not yet available for the garment industry as such. In our study we did not encounter these subcategories in the supply chains.

country	Minimum Wage* (int \$ PPP/hr)	Fair Wage Deficit FWD (euro/hr)	Extreme Poverty EP (euro/hr)	Occupational Safety & Health OSH (euro/hr)	S-eco-costs Total (euro/hr)
Bangladesh general industry	0.25	in Extr. Poverty	26.17	1.61	27.78
Bangladesh garment industry	0.90	4.06	0	1.61	5.67
Belgium	10.31	0	0	0.84	0.84
China	1.99	3.15	0	0.99	4.14
India	1.02	3.96	0	1.19	5.15
Indonesia	1.14	3.86	0	1.14	5.00
Myanmar	0.46	in Extr. Poverty	18.14	1.82	19.96
Pakistan	2.04	3.11	0	1.12	4.23
Sri Lanka	0.81	in Extr. Poverty	4.77	1.14	5.91
Thailand	2.86	2.43	0	1.48	3.91
Turkey	4.30	1.24	0	1.00	2.24
Vietnam	1.52	3.54	0	1.49	5.03
United States	7.25	0	0	0.80	0.80

* (Trading Economics, 2015)

The countries for the three cases in the final section are in bold

Table 1 The s-eco-costs in euro per hour for some leading countries in the textile industry

3.2 S-LCA of two textile products for three different supply chains

3.2.1 Goal and scope of the S-LCA study

The goal of the study is to benchmark production processes and production chains for a T-shirt and a pair of jeans. Three supply chains are analysed: a Western (W) garment chain located with cotton production in the USA and fabric and garment production in Belgium in the EU; an Asian (A) chain in India/Bangladesh (with minimum wages for Bangladesh industry in general); and an Asian Best Practice (ABP) chain in China/India/Bangladesh (with minimum wages for Bangladesh garment industry).

The scope is a cradle-to-gate analysis with a system boundary for the S-LCA, as depicted in Fig. 4.

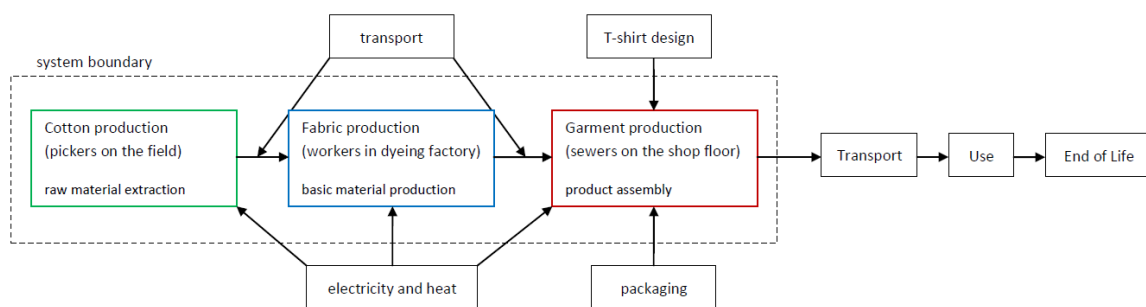


Fig. 4 The S-LCA system under study for a T-shirt (or, similarly, a pair of jeans)

The declared unit is either one T-shirt as defined in Annex A Table 7, or one pair of jeans as defined in Table 8.

The 3 production chains with the geographical locations of each production step are depicted in Fig. 5.

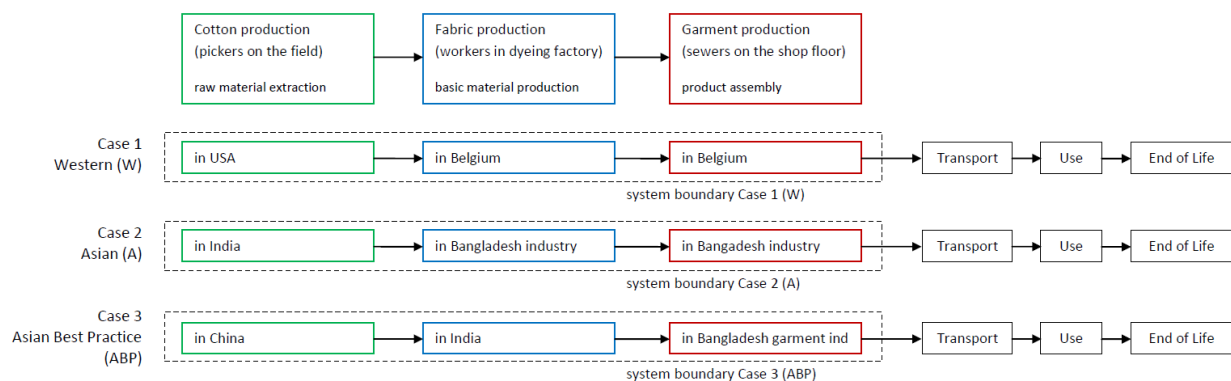


Fig. 5 The 3 different supply chains of the system under study, each with 2 reference flows (1 T-shirt and 1 pair of jeans)

3.2.2 The Life Cycle Inventory and the Life Cycle Impact Assessment

The s-eco-costs for the production stages of a T-shirt are calculated from the hours required in the production processes (calculated from Annex A Table 9, shown in the first column of Table 2), combined with the s-eco-costs per hour (for country level see Table 1). Table 2 gives the results of these calculations.

In the cases we studied, the companies adhered to the local legislation, so we did not encounter Child Labour and Extreme Working Hours, which is the reason that these subcategories are not included in our study.

Process	T-shirts per hour	Fair Wage Deficit (€/T-shirt)	Extreme Poverty (€/T-shirt)	OSH (€/T-shirt)	Total (€/T-shirt)
Cotton production standard, India	87.9	0.045	0	0.014	0.059
Bio-cotton production, India	87.9	0.043	0	0.014	0.056
Cotton prod. Best Practice, China	87.9	0.036	0	0.011	0.047
Fabric production standard, Vietnam	2016	0.002	0	0.001	0.002
Fabric production standard, Bangladesh	2016	in Extreme Poverty	0.013	0.001	0.014
Fabric prod. Best Practice, India	2016	0.002	0	0.001	0.003
Garment production stand., Bangladesh	20	in Extreme Poverty	1.308	0.081	1.389
Garment prod. min. wage Myanmar	20	in Extreme Poverty	0.907	0.091	0.998
Garment prod. Best Practice Bangladesh	20	0.203	0	0.081	0.284

prod. = production; stand. = standard

the numbers for the three cases in the subsequent section are in bold

Table 2 The s-eco-costs scores (in €/piece) for specific production stages of a T-shirt

The overall calculations for T-shirts (and jeans) are summarised in Table 3 for the production chains as specified in Fig.5. The difference between Case 2 (the Asian route) and Case 3 (the Best Practice Asian route) is caused by the fact that the workers in the cotton field are better paid in China than in India, and that we assumed that the work in Bangladesh in Case 2 is done by subcontractors which do not pay the minimum wage of garment industry, but pay the minimum wage of the general industry (which is considerably lower, see Table 1).

The calculations which lead to the results for jeans in Table 3 are similar to the calculations of the T-shirts: the difference is that jeans requires more production hours.

Indicator	Case 1 (W) T-shirt (€/T-shirt)	Case 2 (A) T-shirt (€/T-shirt)	Case 3 (ABP) T-shirt (€/T-shirt)	Case 1 (W) jeans (€/jeans)	Case 2 (A) jeans (€/jeans)	Case 3 (ABP) jeans (€/jeans)
Fair Wage Deficit	0	0.045	0.241	0	0.135	1.918
Extreme Poverty	0	1.321	0	0	11.668	0
Occ. Safety&Health	0.046	0.095	0.092	0.384	0.759	0.755
S-eco-costs total	0.046	1.461	0.333	0.384	12.561	2.674

Table 3 The s-eco-costs (in €/piece) of a T-shirt and a pair of jeans for different production chains

4. Discussion

The authors of this paper are aware of the fact that it is an arduous task to quantify S-LCA results in a single indicator, however, quantification cannot be avoided in LCA benchmarking and practical decision taking processes, where trade-off of different (sub)categories is often required. UNEP/SETAC (2009, p.72) allows for quantification: “a scoring system may be used to help assess the ‘meaning’ of the inventory data, based on performance reference points” ... “the scoring and weighting system must be well defined and transparent”. The issue is that a transparent system of performance reference points and scoring systems is per definition subjective (‘value based’). The consequence is that the s-eco-costs scoring system cannot be seen as ‘the absolute truth’, but must be regarded as a structured calculation method, where the user might deviate from the proposed default multiplication factors and performance reference points, when he or she thinks that there is a need for.

The most relevant issue is the question to what extent is it allowed to apply s-eco-costs.

Jørgensen (2014) argues that an unsustainable supplier might lose its supply contract as a result of S-LCA, which is for Jørgensen a reason to *refrain* from making an S-LCA (since the positive and negative effects of it are too complex). Indeed the described situation in his paper is negative on micro scale for the local community; however, it is positive for sustainable suppliers in a country on the long run, which is what we need in the required transition towards a more sustainable society.

On the level of countries, the situation is more complex. In the garment industry, there is a severe competition between countries to attract foreign investors. Foreign garment factory owners, however, threaten governments to leave the country when the minimum wages are set too high (Reuters, 2015). The only way out is the trend that big retailers (e.g. Hennes & Mauritz and Gap) force countries to take action for a better minimum wage and still purchase in that country. Therefore we plead for making S-LCAs, so that the unsocial issues in the production chain become transparent, provided that the use and communication of it will be done with care.

Arvidsson et al. (2015) argue that Child Labour is necessary in extreme poor families to be able to buy enough food, so child labour should *not* be incorporated in S-LCA since this issue is too complex to handle. The argument makes sense on the micro scale of the family and possibly in the short-term. But on a macro scale and in the long run the deployment and exploitation of children in supply chains may not be ignored and must be prevented. Likewise illegal production chains must be eradicated, which can be considered as one of the (corporate social) responsibilities of the retail industry in developed world. We therefore include the Child

Labour indicator in our metrics, to demonstrate the importance - and the external costs - of this category, and to provide a means to quantitatively benchmark between different supply chains.

A second issue is the question whether the multipliers in s-eco-costs are too low or too high. The general policy in s-eco-costs is to take the high (safe) side. The PRP of the fair wage may be taken a factor two lower (see Fig. 2) but that seems to be far from safe side. The issue of the indicator choice for child labour (1 full year of child labour = 1 DALY) has been dealt with in Section 2.3.3: it must be regarded as a default value, which should be refined when a quantitative rating system for types of child labour becomes available in science.

The price of a DALY may be disputed, but we do not enter here in the wide discussion on it in medical science. The consensus in the USA as well as in Europe seems to be the 80.000 euro plus or minus approximately 20%. We adhere to the idea that a life in Bangladesh is of equal value as a life in Europe, and therefore we take the ‘revealed preference’ of the European people.

The third issue is how these s-eco-costs compare to the eco-costs of E-LCA (see Fig. 1).

Data on E-LCA of garments are provided in (Van der Velden et al, 2014) for ReCiPe points, carbon footprint and eco-costs per kg. Estimates of data for a T-shirt and a pair of jeans are provided in Table 4.

Indicator	Case 1 (W) T-shirt (€/piece)	Case 2 (A) T-shirt (€/piece)	Case 3 (ABP) T-shirt (€/piece)	Case 1 (W) jeans (€/piece)	Case 2 (A) jeans (€/piece)	Case 3 (ABP) jeans (€/piece)
Human Toxicity	0.03	0.04	0.04	0.08	0.12	0.11
Eco-toxicity	0.11	0.18	0.14	0.34	0.55	0.44
Resource Depletion	0.18	0.21	0.21	0.54	0.64	0.64
Carbon Footprint	0.27	0.31	0.28	0.82	0.93	0.86
Eco-costs total	0.59	0.74	0.67	1.78	2.25	2.05

Table 4 The eco-costs (in €/piece) of a T-shirt and a pair of jeans, cradle-to-gate

It may be concluded from Table 3 and Table 4 that the social un-sustainability of the Asian production chains seems to be of higher importance than the environmental sustainability from the point of view of external costs, but that does not mean that we should pay no attention to the environmental issue. Recent LCA studies (Roos et al, 2015b; Van der Velden et al, 2014), show the real hotspots in modern garment chains, enable benchmarking, and reveal that the use phase is not anymore the main hotspot, as was claimed by Allwood (2006). The responsibility is widely acknowledged by the garment industry (SAC, 2015), however, until now it is hard to check the reliability of benchmarks (Made-by, 2015; EPL Kering, 2015) and scorecards (Nike, 2013) in the sector, mainly because of in-transparency, lack of underlying data presentation and scientific basis, and system

flaws. It would be beneficial for the garment industry when they adopt scientific LCA as a reliable and trustworthy method, rather than inventing their own biased metrics in which their own products seem to score better than in the scientific LCA indicators.

The fourth issue is how the s-eco-costs compare to the price of T-shirts and jeans. The cheapest price for T-shirts in European discount shops is around 2 euro, the high-end brands sell for 30 – 80 euro. When the minimum fair wage is paid to all people in the production chain, the total extra production costs per T-shirt would be around 0.43 euro (and 3.36 euro for a pair of jeans), excluding VAT and profit margin. This would not be any problem for high-end brands as such: the consumers who buy these brands are, in general, prepared to pay a few cents more for ‘clean’ clothes. For the discount shops, however, these extra production costs will increase their sales price considerably, which reveals a conflict of interest between the poor people in the developing world and the poor people in Europe who buy these shirts.

Note 1. Fashion companies have been heavily criticized - mainly by NGOs, but increasingly by authorities and consumers after the Rana Plaza collapse on April 24 2013 - for unsocial operational management in their upstream supply chain. We would like to highlight here that these companies have restricted purchasing power, because of invisible subcontracting in the textile and garment producing countries: garments are often not made where you think they are made. Exactly the same issue of subcontracting is as well a thread for correct s-eco-costs calculations. Therefore it is important to track and trace the specific garment flow and collect the right data (not only via the management of the suppliers, but also from the workers themselves).

It is because of this subcontracting that we found not much evidence that the agreed minimum wage by the big garment companies is really getting in the hands of the shop floor workers.

Note 2. We ascertain that in practice there are many difficulties in measuring corruption, as well as other unsocial circumstances like discrimination and inequality. Our attempt to develop a midpoint system for safety in buildings (to quantify the Rana Plaza type of risk) failed so far: a simple PRP could not be defined.

5. Conclusions

The s-eco-costs system as presented in this paper provides a lot of transparency in the complex issue of social sustainability in the developing world in general, and in the garment production cases under study.

The general assessment based on minimum wages in several countries with textile industry shows that the total s-eco-costs of Bangladesh (€ 27.78 per hour, based on the average minimum wage of 0.25 int \$ PPP per hour, paid to workers in Bangladesh) and Myanmar (€ 19.96) substantially exceed those of the other countries (see Table 1). Furthermore the total s-eco-costs (ad € 5.67) of the Best Practice situation in the Bangladesh textile industry (when the workers are paid 0.90 int \$ PPP per hour, based on the minimum wage for the garment industry in that country) are on the same level as Sri Lanka, India and Vietnam (€ 5.91; € 5.15 and € 5.03 per hour respectively). Belgium and the USA show the lowest outcomes (€ 0.84 and € 0.80 per hour) due to the s-eco-costs of Occupational Safety and Health only.

On the product-level of a T-shirt, the cradle-to-gate s-eco-costs calculations point out the garment production phase (the sewers on the shop floor) in Bangladesh and Myanmar as the social hotspot (total s-eco-costs per T-shirt are € 1.39 and € 1.00; see Table 3).

The s-eco-costs over the life cycle of a pair of jeans show a similar pattern as the s-eco-costs of a T-shirt. The total s-eco-costs for a pair of jeans are about eight times higher than those for T-shirts (see Table 4). Even for the Asian Best Practice cases for T-shirts and jeans, the total s-eco-costs are relatively high compared to the US/Europe situation (about seven times higher).

With the presentation and validation of the s-eco-costs method in this paper we aim to accelerate further development of the S-LCA method, for hotspot analyses and benchmarking of unsustainable production chains.

We realize this study is limited to just one ('worker') of the five stake-holder categories of UNEP/SETAC (2009), but we think that it does make sense to focus on this category at first.

We hope the way of thinking behind this s-eco-costs method will be inspiring for accelerated method development for quantitative assessment of social sustainability aspects of (clothing) products.

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References

Allwood JM, Laursen SE, Malvido de Rodríguez C, Bocken NM (2006) Well dressed? The present and future sustainability of clothing and textiles in the United Kingdom. University of Cambridge Institute for Manufacturing

Arvidsson R, Baumann H, Hildenbrand J (2015) On the scientific justification of the use of working hours, child labour and property rights in social life cycle assessment: three topical reviews. *Int J Life Cycle Assess* 20(2):161–173

Benoît Norris C (2014) Data for social LCA. *Int J Life Cycle Assess* 19(2):261-265

Berik G, Rodgers Y D M (2010) Option for Enforcing labour standards: lesson from Bangladesh and Cambodia. *J of Int Dev* 85(22): 56–85

BLS (2013) Nonfatal Occupational Injuries and Illnesses requiring Days Away From Work, 2012. Bureau of Labor Statistics U.S. Department of Labor. Available at: http://www.bls.gov/news.release/archives/osh2_11262013.pdf

Bocoum I, Macombe C, Revéret JP (2015) Anticipating impacts on health based on changes in income inequality caused by life cycles. *Int J Life Cycle Assess* 20(3):405-417

Choudhury AR (2014) Environmental Impacts of the Textile Industry and Its Assessment Through Life Cycle Assessment. In: Muthu SS (ed) *Roadmap to Sustainable Textiles and Clothing*. Springer, Singapore, pp 1-39

Cleemput I, Neyt M, Thiry N, De Laet C, Leys M (2011) Using threshold values for cost per quality-adjusted life-year gained in healthcare decisions. *Int J Technol Assess Health Care* 27(1): 71-76

CLW (2012) *Tragedies of Globalization: The Truth Behind Electronics Sweatshops*. China Labour Watch, New York

Croes PR, Vermeulen WJV (2016a) In search of income reference points for SLCA using a country level sustainability benchmark (part 1): fair inequality. A contribution to the Oiconomy project. *Int J Life Cycle Assess* 21(3): 349–362

Croes PR, Vermeulen WJV (2016b) In search of income reference points for SLCA using a country level sustainability benchmark (part 2): fair minimum wage. A contribution to the Oiconomy project. *Int J Life Cycle Assess* 21(3): 363–377

Dustmann C, Casanova M, Fertig M, Preston I, Schmidt CM (2003) The impact of EU enlargement on migration flows. Research Development and Statistics Directorate, Home Office, Online Report No. 25/03

Ekener-Petersen E, Finnveden G (2012) Potential hotspots identified by social LCA—part 1: a case study of a laptop computer. *Int J Life Cycle Assess* 18(1): 127–143

EPL Kering (2015) <http://www.kering.com/en/sustainability/epl>. Accessed 28 September 2015

Franze J, Ciroth A (2011) A comparison of cut roses from Ecuador and the Netherlands. *Int J Life Cycle Assess* 16(4):366–379

Grosse SD (2008) Assessing cost-effectiveness in healthcare: history of the \$50,000 per QALY threshold. *Expert Rev of Pharmacoeconomics & Outcomes Res*, 8(2):165-178

Helliwell J, Layard R, Sachs J (2013) *World Happiness Report 2013*. New York: UN Sustainable Development Solutions Network. Full text and supporting documentation can be downloaded from the UN SDSN website (www.unsdsn.org)

Holland D, Fic T, Rincon-Aznar A, Stokes L, Paluchowski P (2011) *Labour mobility within the EU: The impact of enlargement and the functioning of the transitional arrangements, final report*. National Institute of Economic and Social Research, London

Hosseinijou S, Mansour S, Shirazi M (2014) Social life cycle assessment for material selection: a case study of building materials. *Int J Life Cycle Assess* 19(3):620–645

ILO (2003) *Occupational accidents and work related diseases, 2003*. Available at: http://www.ilo.org/moscow/areas-of-work/occupational-safety-and-health/WCMS_249278/lang--en/index.htm

ILO (2013) Marking progress against child labour. Global estimates and trends 2000-2012. International Labour Office. Available at: http://www.ilo.org/wcmsp5/groups/public/---ed_norm/---ipec/documents/publication/wcms_221513.pdf

ILO (2014) Wages and Working Hours in the Textiles, Clothing, Leather and Footwear Industries. International Labour Office. Geneva

ILO (2015) World Report on Child Labour. International Labour Office. Available at: <http://www.ilo.org/ipeinfo/product/download.do?type=document&id=26977>

ISO (2006a) ISO 14040 Environmental management—life cycle assessment—principles and framework. International Organisation for Standardisation (ISO), Geneva

ISO (2006b) ISO 14044 Environmental management—life cycle assessment—requirements and guidelines. International Organisation for Standardisation (ISO), Geneva

Jørgensen A (2014) Social LCA—a way ahead? *Int J Life Cycle Assess* 18(2):296–299

Kelly (2014) Uzbekistan ban on child labour forces more adults into cotton workforce. *TheGuardian* 14-11-2014

King JT, Tsevat J, Lave JR, Roberts MS (2005) Willingness to pay for a quality-adjusted life year: Implications for societal health care resource allocation. *Méd Decision Mak* 25(6):667–677

Kloepffer W (2008) Life cycle sustainability assessment of products. *Int J Life Cycle Assess* 13(2):89–95

Lehmann A, Zschieschang E, Traverso M, Finkbeiner M, Schebek L (2013) Social aspects for sustainability assessment of technologies—challenges for social life cycle assessment (SLCA). *Int J Life Cycle Assess* 18(8):1581–1592

Lenzing (2015) <http://www.lenzing.com/en/fibers/the-global-fiber-market.html>. Accessed 7 July 2015

Made-by (2015) <http://www.made-by.org/consultancy/tools/environmental/>. Accessed 28 August 2015

Manik Y, Leahy J, Halog A (2013) Social life cycle assessment of palm oil biodiesel: a case study in Jambi Province of Indonesia. *Int J Life Cycle Assess* 18(7):1386–1392

Mariani R D (2013) Working conditions in the Bangadeshi garment sector: social dialogue and compliance. MSc thesis. Faculty Technology Policy and Management. Delft University of Technology

- Martínez-Blanco J, Lehmann A, Muñoz P, Antón A, Traverso M, Rieradevall J, Finkbeiner M (2014) Application challenges for the social Life Cycle Assessment of fertilizers within life cycle sustainability assessment. *J Clean Prod* 69:34-48
- Mattioda RA, Mazzi A, Canciglieri O, Scipioni A (2015) Determining the principal references of the social life cycle assessment of products. *Int J Life Cycle Assess* 20(8):1155-1165
- Nieminen E, Linke M, Tobler M, Vander Beke B (2007) EU COST Action 628: life cycle assessment (LCA) of textile products, eco-efficiency and definition of best available technology (BAT) of textile processing. *J Clean Prod* 15(13):1259-1270
- NIH (2012) U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES National Institutes of Health. Kidney Disease Statistics for the United States, NIH Publication No. 12–3895 June 2012
- Nike (2013) <http://msi.apparelcoalition.org/#/materials>. Accessed 28 September 2015
- OECD (2011) OECD Better life Compendium initiative of Well-being Indicators. Available at <http://www.oecd.org/general/compendiumofoecdwell-beingindicators.htm>
- OECD (2012) OECD Economic Surveys: European Union 2012, OECD Publishing. doi:10.1787/eco_surveys-eur-2012-5-en. Available at: http://www.oecd-ilibrary.org/economics/oecd-economic-surveys-european-union-2012_eco_surveys-eur-2012-en
- OECD (2015) Purchasing Power Parity Data. Available at: http://stats.oecd.org/Index.aspx?datasetcode=SNA_TABLE4
- Parent, J, Cucuzzella C, Revéret JP (2010). Impact assessment in SLCA: sorting the SLCIA methods according to their outcomes. *Int J Life Cycle Assess* 15(2):164–171
- Reuters (2015) Press release “Myanmar sets \$2.80 daily minimum wage in bid to boost investment”, available at <http://www.reuters.com/article/2015/08/29/us-myanmar-economy-wages-idUSKCN0QY0A620150829>
- Roos S, Posner S, Jönsson C, Peters GM (2015a) Is Unbleached Cotton Better Than Bleached? Exploring the Limits of Life-Cycle Assessment in the Textile Sector. *Cloth Text Res J*. doi:0887302X15576404
- Roos S, Sandin G, Zamani B, Peters G (2015b) Environmental assessment of Swedish fashion consumption. Five garments – sustainable futures. Mistra Future Fashion Deliverable No: D2.6
- Rosenbaum RK, Bachmann TM, Swirsky Gold L, Huijbregts MAJ, Jolliet O, Juraske R, Koehler A, Larsen HF, MacLeod M, Margni M, McKone TE, Payet J, Schuhmacher M, Van de Meent D,

Hauschild MZ (2008). USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. *Int J Life Cycle Assess* 13(7):532-546

Round Table for Product Social Metrics (2014) Handbook for Product Social Impact Assessment. Available at: <http://product-social-impact-assessment.com/wp-content/uploads/2014/08/Handbook-for-Product-Social-Impact-Assessment.pdf>

RVZ (2006) Raad voor Volksgezondheid en Zorg: Zinnige en Duurzame Zorg. (in Dutch). Available at: http://www.rvz.net/uploads/docs/Advies_-_Zinnige_en_duurzame_zorg.pdf

SAC (2015) www.apparelcoalition.org. Accessed January 2015

Shen L, Worrell E, Patel MK (2010) Environmental impact assessment of man-made cellulose fibres. *Resour Conservation Recycl* 55(2):260-274

Singh S, Singh S, Pannu C J S, Singh J (2000) Optimization of energy input for raising cotton crop in Punjab. *Energy Conversion and Management*, 41(17):1851-1861

Steinberger JK, Friot, D, Joliet O, Erkman S (2009) A spatially explicit life cycle inventory of the global textile chain. *Int J Life Cycle Assess* 14(5):443-455

Terinte N, Manda BMK, Taylor J, Schuster KC, Patel MK (2014) Environmental assessment of coloured fabrics and opportunities for value creation: spin-dyeing versus conventional dyeing of modal fabrics. *J Clean Prod* 72:127-138

Trading Economics (2015) Minimum wages. Available at: <http://www.tradingeconomics.com/country-list/minimum-wages>, accessed at 15-09-2015

UNEP/SETAC (2009) Guidelines for Social Life Cycle Assessment of Products. Available at: http://www.unep.org/pdf/DTIE_PDFS/DTIx1164xPA-guidelines_sLCA.pdf

UNEP/SETAC (2011) Towards a Life Cycle Sustainability Assessment. Available at: http://www.unep.org/pdf/UNEP_LifecycleInit_Dec_FINAL.pdf

Van der Velden NM, Patel MK, Vogtländer JG (2014) LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane. *Int J Life Cycle Assess* 19(2):331-356

Van der Velden NM, Kuusk K, Köhler AR (2015) Life cycle assessment and eco-design of smart textiles: The importance of material selection demonstrated through e-textile product redesign. *Mater Des* 84:313-324

Vogtländer JG, Brezet HC, Hendriks CF (2001) The virtual eco-costs '99 A single LCA-based indicator for sustainability and the eco-costs-value ratio (EVR) model for economic allocation. *Int J Life Cycle Assess* 6(3):157-166

Vogtländer JG, Bijma A, Brezet HC (2002) Communicating the eco-efficiency of products and services by means of the eco-costs/value model. *J Clean Prod* 10(1):57-67

Vogtländer JG, Van der Velden NM, Van de Lugt P (2014) Carbon sequestration in LCA, a proposal for a new approach based on the global carbon cycle; cases on wood and on bamboo. *Int J Life Cycle Assess* 19(1):13–23

Wageindicator Foundation (2015) Minimum wages. Available at:
<http://www.wageindicator.org/main/salary/minimum-wage>

WHO (2004) Disability Weights For Diseases and Conditions. Available at:
http://www.who.int/healthinfo/global_burden_disease/GBD2004_DisabilityWeights.pdf

Yuan ZW, Zhu YN, Shi JK, Liu X, Huang L (2013) Life-cycle assessment of continuous pad-dyeing technology for cotton fabrics. *Int J Life Cycle Assess* 18(3):659-672

Zhang Y, Liu X, Xiao R, Yuan Z (2015) Life cycle assessment of cotton T-shirts in China. *Int J Life Cycle Assess* 20(7):994-1004

Tables

country	Minimum Wage* (int \$ PPP/hr)	Fair Wage Deficit FWD (euro/hr)	Extreme Poverty EP (euro/hr)	Occupational Safety & Health OSH (euro/hr)	S-eco-costs Total (euro/hr)
Bangladesh general industry	0.25	in Extr. Poverty	26.17	1.61	27.78
Bangladesh garment industry	0.90	4.06	0	1.61	5.67
Belgium	10.31	0	0	0.84	0.84
China	1.99	3.15	0	0.99	4.14
India	1.02	3.96	0	1.19	5.15
Indonesia	1.14	3.86	0	1.14	5.00
Myanmar	0.46	in Extr. Poverty	18.14	1.82	19.96
Pakistan	2.04	3.11	0	1.12	4.23
Sri Lanka	0.81	in Extr. Poverty	4.77	1.14	5.91
Thailand	2.86	2.43	0	1.48	3.91
Turkey	4.30	1.24	0	1.00	2.24
Vietnam	1.52	3.54	0	1.49	5.03
United States	7.25	0	0	0.80	0.80

* (Trading Economics, 2015)

The countries for the three cases in the final section are in bold

Table 1 The s-eco-costs in euro per hour for some leading countries in the textile industry

Process	T-shirts per hour	Fair Wage Deficit (€/T-shirt)	Extreme Poverty (€/T-shirt)	OSH (€/T-shirt)	Total (€/T-shirt)
Cotton production standard, India	87.9	0.045	0	0.014	0.059
Bio-cotton production, India	87.9	0.043	0	0.014	0.056
Cotton prod. Best Practice, China	87.9	0.036	0	0.011	0.047
Fabric production standard, Vietnam	2016	0.002	0	0.001	0.002
Fabric production standard, Bangladesh	2016	in Extreme Poverty	0.013	0.001	0.014
Fabric prod. Best Practice, India	2016	0.002	0	0.001	0.003
Garment production stand., Bangladesh	20	in Extreme Poverty	1.308	0.081	1.389
Garment prod. min. wage Myanmar	20	in Extreme Poverty	0.907	0.091	0.998
Garment prod. Best Practice Bangladesh	20	0.203	0	0.081	0.284

prod. = production; stand. = standard

the numbers for the three cases in the subsequent section are in bold

Table 2 The s-eco-costs scores (in €/piece) for specific production stages of a T-shirt

Indicator	Case 1 (W) T-shirt (€/T-shirt)	Case 2 (A) T-shirt (€/T-shirt)	Case 3 (ABP) T-shirt (€/T-shirt)	Case 1 (W) jeans (€/jeans)	Case 2 (A) jeans (€/jeans)	Case 3 (ABP) jeans (€/jeans)
Fair Wage Deficit	0	0.045	0.241	0	0.135	1.918
Extreme Poverty	0	1.321	0	0	11.668	0
Occ. Safety&Health	0.046	0.095	0.092	0.384	0.759	0.755
S-eco-costs total	0.046	1.461	0.333	0.384	12.561	2.674

Table 3 The s-eco-costs (in €/piece) of a T-shirt and a pair of Jeans for different production chains

Indicator	Case 1 (W) T-shirt (€/piece)	Case 2 (A) T-shirt (€/piece)	Case 3 (ABP) T-shirt (€/piece)	Case 1 (W) jeans (€/piece)	Case 2 (A) jeans (€/piece)	Case 3 (ABP) jeans (€/piece)
Human Toxicity	0.03	0.04	0.04	0.08	0.12	0.11
Eco-toxicity	0.11	0.18	0.14	0.34	0.55	0.44
Resource Depletion	0.18	0.21	0.21	0.54	0.64	0.64
Carbon Footprint	0.27	0.31	0.28	0.82	0.93	0.86
Eco-costs total	0.59	0.74	0.67	1.78	2.25	2.05

Table 4 The eco-costs (in €/piece) of a T-shirt and a pair of jeans, cradle-to-gate

Figure captions

- Fig. 1** Structure of the eco-costs and the s-eco-costs
- Fig. 2** Percentage of population migrated after the accession in the EU as a function of relative minimum wage
- Fig. 3** The s-eco-costs as a function of the wage
- Fig. 4** The S-LCA system under study for a T-shirt (or, similarly, a pair of jeans)
- Fig. 5** The 3 different supply chains of the system under study, each with 2 reference flows
(1 T-shirt and 1 pair of jeans)

Figures

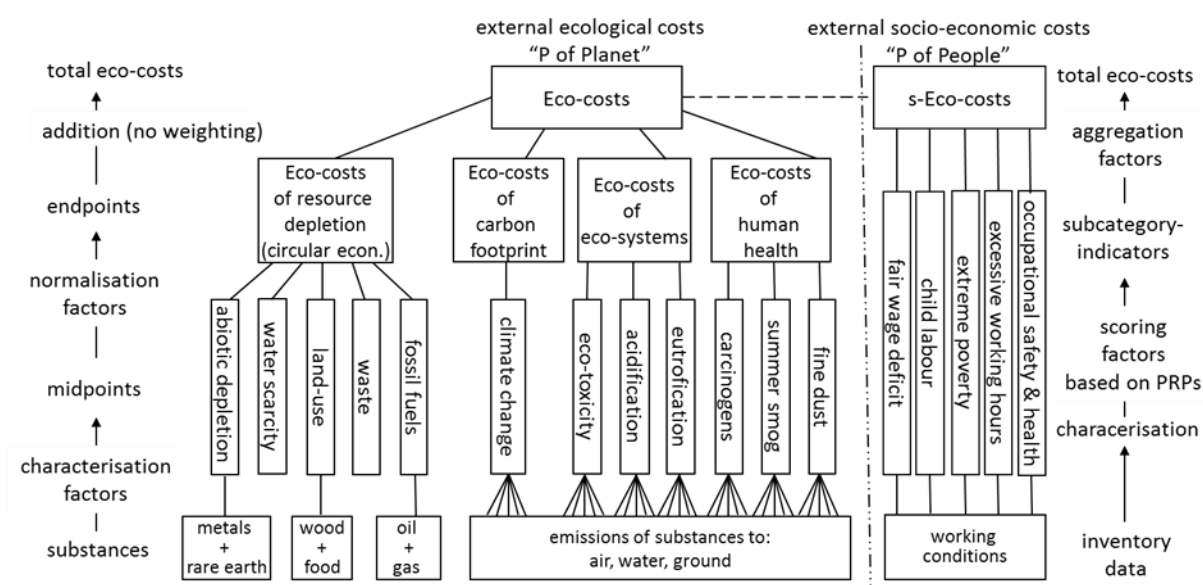


Fig. 1 Structure of the eco-costs and the s-eco-costs

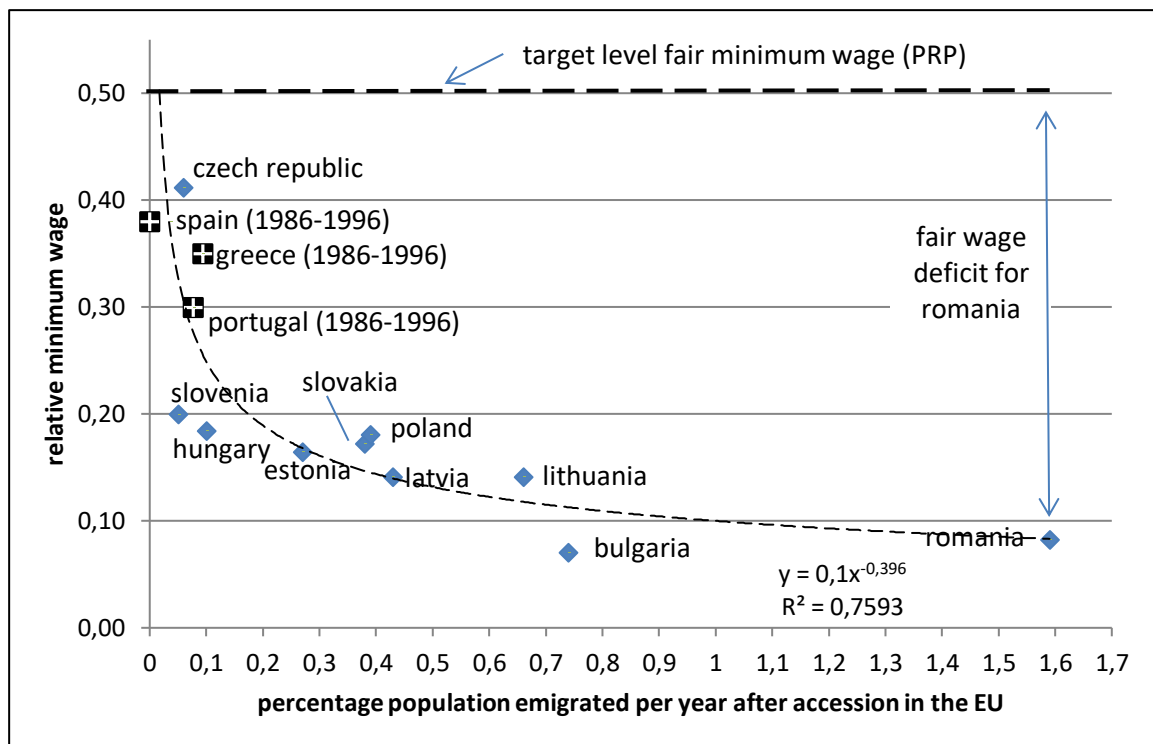


Fig. 2 Percentage of population migrated after the accession in the EU as a function of relative minimum wage

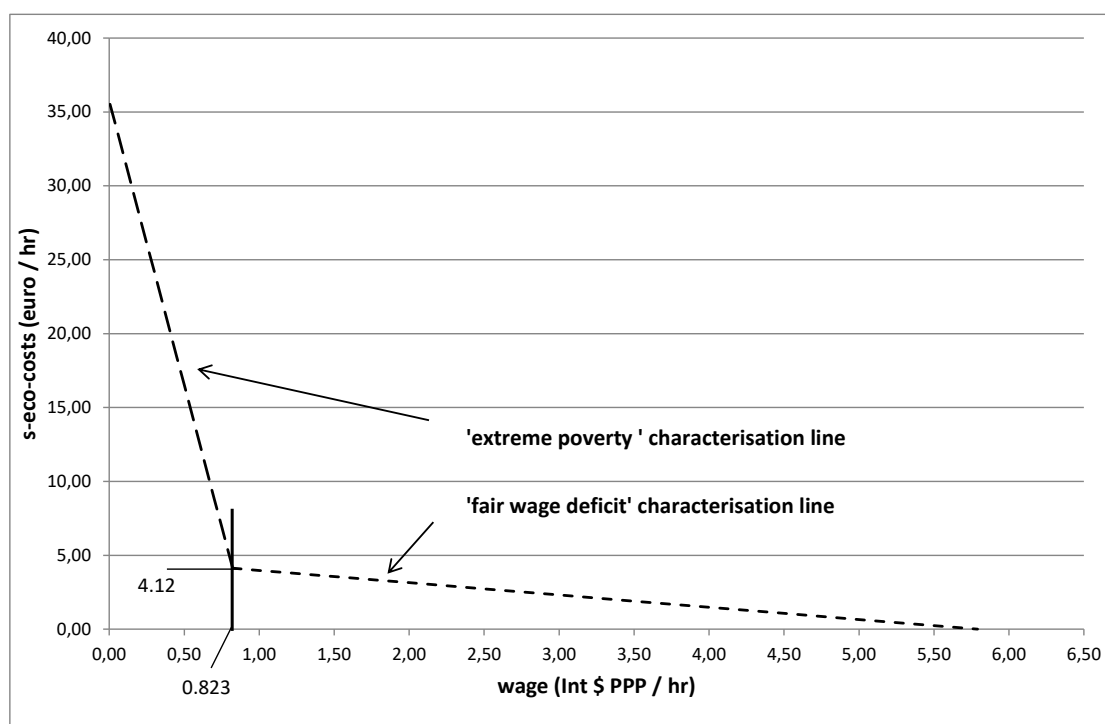


Fig. 3 The s-eco-costs as a function of the wage

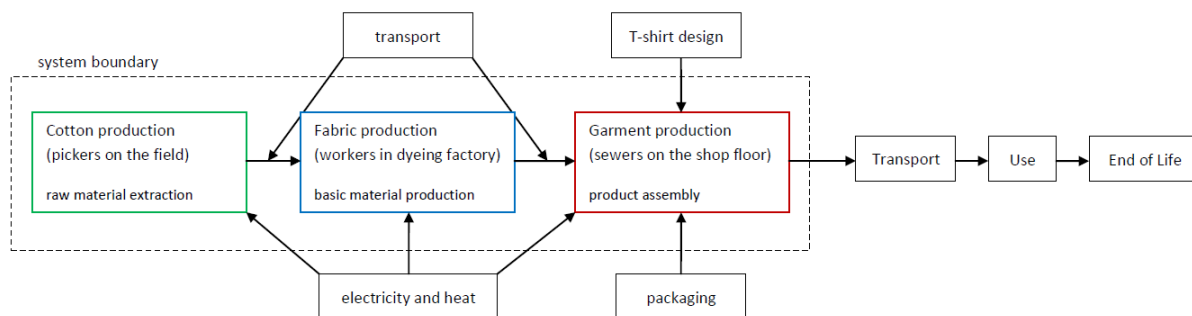


Fig. 4 The S-LCA system under study for a T-shirt (or, similarly, a pair of jeans)

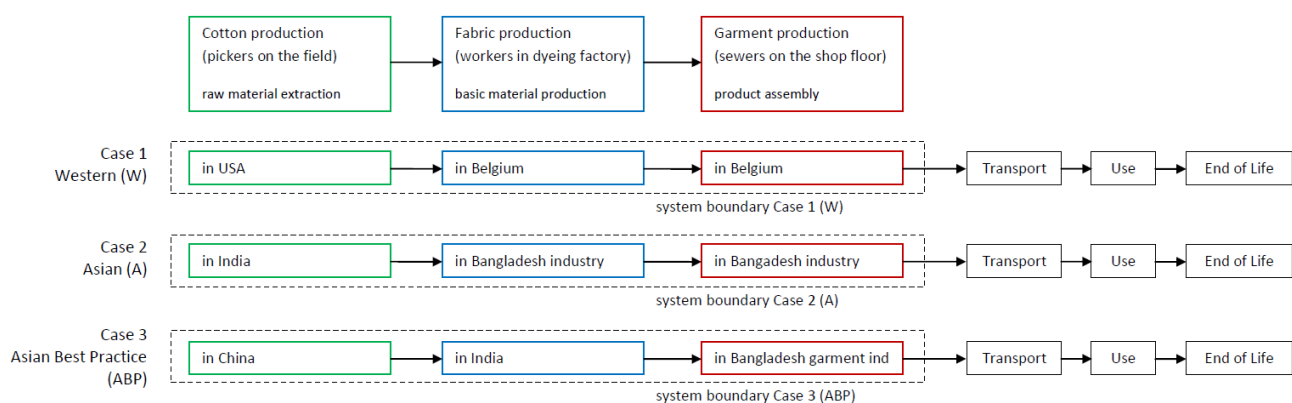


Fig. 5 The 3 different supply chains of the system under study, each with 2 reference flows (1 T-shirt and 1 pair of jeans)

Annex A

	inside Europe	outside Europe (ILO-norms)	max hours Child Labour (agriculture, service and domestic work)
hours per day	8	8	2
days per week	5	6	6
hours per week	40	48	12
weeks per year	46	49	49
days per year	230	280	280
hours per year	1840	2240	560

Table 6 Norms for working hours

fabric: single jersey T-shirt knit produced via circular knitting				
density fabric	0.160	kg/m ²		
weight T-shirt	0.150	kg		
yarn count	200	dtex		
finished fabric needed for making up	0.158	kg	5%	making up waste*
finished fabric needed for cutting	0.165	kg	5%	cutting waste*
greige knitted fabric needed for finishing	0.174	kg	5%	finishing waste*
yarn needed	0.177	kg	2%	knitting waste*
raw cotton fibre needed	0.182	kg	2.50%	spinning waste*
seed cotton needed (machine picking)	0.309	kg	41%	picking waste**
seed cotton needed (hand picking)	0.213	kg	15%	picking waste**

*waste percentage verified by Han Hamers via personal communication d.d. 07-09-2015

** waste volumes for ginning - mainly plant residues - derived from: Ellebæk Larsen S, Hansen J et al (2007) EDIPTEX–Environmental assessment of textiles. Danish Ministry of the Environment, Environmental Protection Agency, p 220

Table 7 Specifications of the T-shirt

fabric: woven fabric				
density fabric	333-500	kg/m ²		
weight fabric for jeans	0.450	kg		
yarn count warp/weft	500	dtex		
finished fabric needed for making up	0.473	kg	5%	making up waste*
finished fabric needed for cutting	0.496	kg	5%	cutting waste*
greige woven fabric needed for finishing	0.521	kg	5%	finishing waste*
yarn needed	0.531	kg	2%	weaving waste*
raw cotton fibre needed	0.545	kg	2.50%	spinning waste*
seed cotton needed (machine picking)	0.926	kg	41%	picking waste*
seed cotton needed (hand picking)	0.640	kg	15%	picking waste*

*waste percentages assumed to be equal to the T-shirt

Table 8 Specifications of the pair of jeans

Specification	Reference + remarks
cotton picker picks 150 kg cotton per day	(Singh, 2000; Kelly, 2014) http://www.cottonginmuseum.org/museum.htm , accessed at 22-02-2016; https://www.youtube.com/watch?v=YUmlBm5uoIU&x-yl-cl=84411374&feature=player_embedded&v=YUmlBm5uoIU&x-yl-ts=1421828030 , accessed at 22-01-2015
in a wet finishing factory a worker produces 2000 kg of fabric per 6 hours	personal communication with Han Hamers d.d. 07-09-2015 = 333 kg per hour = [fabric for] 2016 T-shirts or 672 jeans per hour
dressmaker makes 20 T-shirts per hour	personal communication with Han Hamers d.d. 20-02-2015
dressmaker makes 2.25 jeans per hour	personal communication with Erik Toenhake d.d. 20-02-2015
bio-cotton production, India	Reijn G (2015) Ontwikkelingshulp werkt toch. De Volkskrant, 2 September 2015, pp 31: Bio-cotton farmers achieve a 26% higher income than non-bio -; we assumed that this higher income is directly transferred to the workers

Table 9 Extra data used for the calculations of Table 3 and 4

Publication 4: Designing (with) 3D-printed textiles P.4

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Designing with 3D Printed Textiles

A case study of Material Driven Design

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Abstract— This paper describes the findings and results of a design project with the goal to design a wearable garment using 3D Printed textiles, which not only has functional or environmental superiorities, but also experiential ones. The approach that was adopted for this project is a recently developed method on Material Driven Design (MDD), which suggests a number of steps to design meaningful products when a chosen material is the point of departure. As this method has not yet been applied on a project involving additive manufacturing, another goal is to explore how the MDD method can be used in a project where AM is the primary production method. For MDD, this means that the material that is usually the starting point, should now be a combination of material, structure and process (MSP), and that it is important to understand how these aspects influence each other. The final MSP concept can be locally varied to create property gradients, which results in a range of slightly different MSP's. These materials have been embodied in the design of a corselet, which utilizes the different properties of the MSP. A number of recommendations has been given for the development of future 3D Printed MSP's.

Additive manufacturing, textiles, 3D Printed textiles, Material Driven Design, garments

1. INTRODUCTION

Until recently, applications of 3D Printing or Additive Manufacturing (AM) in the field of fashion have been limited to accessories and shoes, instead of garments. This could be explained by the limited set of materials available for AM that showed potential for comfortable garments.

Pioneering work on AM fabrication of fabric-like materials was presented by Evenhuis and Kyttanen (2003), whose method included projecting a textile pattern onto a particular surface, for instance a piece of clothing, and generating a 3-dimensional computer model of the pattern [1]. The result of this process is a complex model of interwoven links, which resembles chainmail structures as used for armour in the Middle Ages.

Since then, the potential for creating textiles by means of AM has mostly been attributed to these structures. They are often called multiple assemblies, since in essence they consist of separate parts [2]. The only limiting factors attributed to these structures are the limitations of existing CAD modelling

tools, for instance the ability to “drape” the AM textile across a curved surface (such as the human body), which was extensively researched by Bingham et al [3], Crookston et al. [4] and Johnson et al. [5]. Proposed applications for these textiles were mainly functional, such as stab-resistant wearables [5] and high-performance or smart textiles [3].

However, the development of flexible materials suitable for AM seems to have renewed interest in other possibilities for the production of 3D Printed textiles. Mikkonen et al. [6] have tested the tensile strength of one of these flexible materials to determine whether it would be a suitable replacement for fabrics.

At the same time, the possibilities of AM have not gone unnoticed in the world of fashion. The form freedom that AM provides has been utilised to create accessories that could not have been created without this technology. Only a few designers have tried their hand at making entire garments using AM. For example, Iris van Herpen, in collaboration with architects such as Beesley and Koerner and designer Neri Oxman, has designed and fabricated numerous sculptural AM garments [7]. These garments were 3D Printed using rigid and flexible materials developed especially for this purpose. The emphasis of such work usually lies on finding a way to translate the vision of the designer and to make a statement, as is common for art, and not in creating objects for daily use. As a result, most of the 3D Printed garments illustrate groundbreaking developments but do not represent comfortable, ready-to-wear clothing. Considering the developments of AM, the potential of using 3D Printed textiles in ready-to-wear garments becomes apparent: they can be more comfortable, personalized and suitable for daily use. In this paper, the findings and results of a design project that addresses this gap are presented.

The ambition of this project was to develop a wearable garment that not only has functional or environmental superiorities (e.g. comfort, personalised, no material waste), but also experiential ones, i.e. how a material/product is perceived by people (e.g. unique tactile experiences, the feeling brought on by unique garments).

The approach is grounded on a recently developed method by Karana et al. (in review) on Material Driven Design (MDD),

which suggests a number of steps to design meaningful products when a material is the departure point. As this method has not yet been applied on a project involving AM, another goal is to explore how the MDD method can be used in a project where AM is the primary production method.

2. METHOD

For this design project, a Material Driven Design (MDD) method was implemented [8]. The goal of the MDD method is to facilitate product design when a material is the main driver. The method is based on developing a thorough understanding of the material in order to reveal the unique qualities that can be emphasized in the final application.

Karana et al. present four main steps in the MDD Method. The first step is centred on gaining an understanding of the material, by performing both a technical characterization as well as an experiential characterization. These can often be performed simultaneously, as they will complement each other. An important part of this step is playing or ‘tinkering’ with the material, to explore its limits. In the second step, a Materials Experience Vision is created. This vision expresses how a designer envisions the role of the material in product design, in relation to the user, product and context. The vision should be related to the unique functional and experiential qualities of the material, as well as to potential of the material for future, unforeseen applications. Such an abstract vision can be hard to relate back to formal material qualities. Therefore, in the third step, the designer can analyse the vision in order to obtain meanings (e.g. high-tech, feminine, cosy, and friendly) that can be translated to material properties using Meaning Driven Material Selection (MDMS) [9]. Finally, in the fourth step, the findings obtained in the previous steps are used to create material/product concepts.

It is important to emphasize that the MDD method has been developed for material driven projects in which a particular material or material family (e.g. oak, cork, a smart composite, bio-plastics, etc.) is used as the point of departure for the design process. In this project, the intention is to explore how this method can be applied in a design project where not only the (type of) material is set, but where AM is defined as the primary production method.

According to MDD 3D Printed textiles are classified as a semi-developed material [8]; a novel material of which the boundaries have not yet been determined. This material can be described as a combination of material, structure, and process (MSP), since these three factors influence each other and the properties of the 3D Printed textile. Therefore, all three are

important to the outcome of the final material. The results of the MDD method can be used to determine the boundaries of this MSP, to find a meaningful application and to give feedback for further development.

3. APPLICATION OF MDD METHOD IN DESIGNING WITH 3D PRINTED TEXTILES

In this section, the application of the MDD method to a design project ‘Designing With 3D Printed Textiles’ is described.

3.1. Understanding the material

In accordance with the MDD method, the first step of the process is understanding the material and characterizing it technically and experientially. It is encouraged to ‘tinker’ with the material, to get insights as to how it behaves.

In order to gain an understanding of the MSP, a number of samples of 3D Printed textiles were obtained. Some samples were collected from AM service providers, designers, and open-source design databases, while others were specifically designed and 3D Printed for this project. Several samples are shown in Fig. 1. This was an iterative process, in which different possible designs were created and their feasibility as a 3D Printed textile was evaluated. It was found that different combinations of MSP result in different materials that can have different, meaningful applications in different contexts.

Three topics were important to understand the context of 3D Printed textiles: the process (i.e. 3D Printing), the product (i.e. textiles), and the MSP itself (i.e. 3D Printed textiles). Since the boundaries of the material had not yet previously been defined, it was necessary to analyse all three domains in order to find its limits and opportunities. This was done by means of literature studies, benchmarking and explorative sessions using the collected and fabricated samples. The most important results of this analysis are summarized below.

a) 3D Printing

Additive Manufacturing or 3D Printing is the collective term for all processes that can form a 3D product by means of adding material, rather than by subtracting material. The information for these products comes from a 3-dimensional computer-aided-design (CAD) model, which is sliced in discrete layers [3]. These slices correspond directly to the layers that are built by the AM process, allowing the production of virtually any geometry. Materials that can currently be processed by AM include polymers, metals and ceramics.

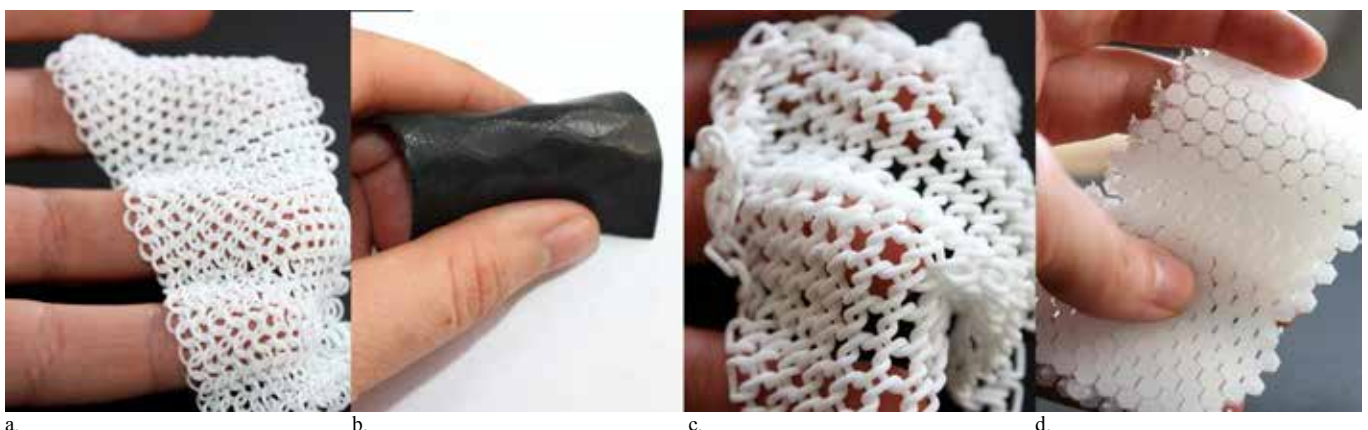


Figure 1. Samples of 3D Printed textiles

The recent developments of AM have set high expectations for the future of this technology. As a result, the tone with which is spoken about 3D Printing in the media is one of excitement, anticipation and innovation, as is consistent with the Gartner Hype Cycle, where 3D Printing is now on its way to the top. Although the positive image of the AM process will most likely contribute to the acceptance of 3D Printed garments, it also means that if the product itself is perceived as not exciting or plain, it could clash with the expectations of the user, which may result in a negative attitude towards the product.

b) Textiles

Flexibility is the most important property for textiles, since without flexibility no wearable garment can be produced. However, there are more properties that are important for textiles, including warmth retention and absorption, softness and elasticity [10], [11], and that make them suitable to wear close to the skin. In order to understand why textiles have these properties, the structure and properties were analysed on four different levels: garment, textile, yarn and fiber. It is possible to distinguish a main structure for each level, which results in a hierarchical structure for the overall material. This hierarchical structure is responsible for most of the mentioned properties that are desirable in textiles, for instance warmth retention is caused by porosity in the structure [10].

However, although the hierarchical structure is important in order to create the desired properties, this brings challenges to the production of this structure. For each structural level, a different production process is necessary, of which the limitations and waste are accumulated across the chain.

c) 3D Printed textiles

Classification

The main requirement for textiles created by means of 3D Printing was found to be flexibility, in order for them to be applied in wearable garments. Therefore, a classification is proposed based on the main source of the flexibility, as depicted in Fig. 2. Structure-based refers to the fact that the flexibility is obtained purely by the application of an appropriate structure, regardless of the material used. This kind of flexibility is obtained by means of discrete bodies that make up multiple assemblies. Material-based refers to the fact that the flexibility is obtained mainly due to the characteristics of the material, by the use of flexible materials such as elastomers. Finally, an overlapping category can be identified in which flexibility is obtained by a designed single body structure that incorporates variable thicknesses, which is named thin structures.

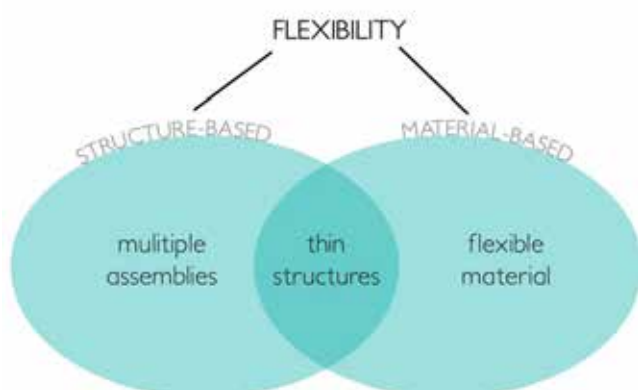


Figure 2. Classification of 3D Printed Textiles

Experiential characterisation

To explore the experiential properties of the material, the collected samples were analysed by means of an explorative user study. In individual sessions >10 participants were shown the collected 3D Printed textile samples. While the participants were invited to touch and interact with the samples, their reactions, remarks, and interactions with the material were evaluated. It was found that the samples elicited movement in order to explore the flexibility of the material, by means of shaking, throwing and caressing the samples. 'Playfulness' and 'surprising' were found as pre-settled meanings, for which the flexibility of the material and the fact that they were 3D Printed contributed most. The latter also elicited a positive reaction, since the 3D Printing process is still perceived as new, exciting, and innovative.

Although all samples were flexible, only one of the samples was explicitly described as a textile by the participants (Fig. 1a). The participants expressed that the fine structure of multiple assemblies made it feel softer and more drapable. The other samples were not seen as textiles. These results indicate that in order for the material to resemble a textile and obtain properties desired for textiles, such as softness and drapability, the macro-structure should be as fine as possible.

In addition to the user studies, following the MDD method, a material benchmark was conducted in order to find examples of AM applied in the area of garments. Most application areas were found in the categories of jewellery and accessories (bags, shoes and hats). In the category of clothing, most application areas were dresses, underwear (corsets), swimwear (bikini) and more sculptural "armours".

3.2. Creating a materials experience vision

After the first step, according to the MDD method it is expected that the designer knows and understands the material. In order to find new, unique applications for the material, it is suggested to create a materials experience vision, which expresses the role of the material in the envisioned user experience, as well as the relation it has to the context [8].

In this design project, the vision is related to the findings from the analysis of the three domains mentioned earlier: 3D Printing, textiles, and 3D Printed textiles.

The use of a new and innovative production process should be utilized to the fullest in order to be of most value. Personalization is one of the key aspects; garments can be produced to the exact measurements of people's bodies, while still being economically viable. Also, the opportunities for including property gradients in the product to be printed (material or structural) are a unique benefit of the process.

Looking at the current life cycle of garments, it becomes clear that it is driven by fluctuations in fashion, which often leads to the early disposal of garments. As a reaction to this, the trend of slow fashion is emerging. Slow fashion is centred on design for long term use and wear, with concern for the entire life cycle of the product [12]. It strives to achieve minimum impact and waste, by increasing the aesthetic, functional and emotional value of the garment [13]. This can be achieved by creating a timeless design that will withstand the influence of fashion. Personalization of a product can

increase its emotional value [14], and thereby prolong its lifespan. From a functional perspective, the product should be a wearable garment that is not obtrusive or hindering in daily activities.

On the material level, this means that the 3D Printed textile should on one hand be suitable for use in garments, and thereby withstand a number of technical requirements, such as flexibility, tear resistance, breathability and water resistance. On the other hand, there are a number of experiential qualities for the material that are related to creating a textile that is comfortable to use. Softness, smoothness, warmth, lustre and coarseness are examples of these qualities.

In this case, a more abstract vision was desired, in order to go beyond the initial findings. The materials experience was formulated as the following statement: I want people to have an attachment to their 3D Printed garment in order to extend its life span, by creating a personally engaging experience, like the act of blowing bubbles. 'Blowing bubbles' is used as a metaphor, illustrating a simple, engaging act that is familiar to everyone. Making the biggest bubbles is a challenge, and watching the light react on them is a pleasure; they are engaging to make and engaging to watch.

3.3. Manifesting materials experience patterns

According to the steps of the MDD method, the vision that was created in the previous step should be further analysed to obtain materials experience patterns [9]. These are obtained by analysing the vision and proposed interaction to distill 'meanings', which in turn can be translated into material properties by applying the Meaning Driven Material Selection (MDMS) method (see [15] for the application of the method).

The meanings were distilled by means of analysing the metaphor and several brainstorm sessions. The two meanings that were thought to best fit the intended interaction were *intriguing* and *familiar*. The meaning *intriguing* is related to the engaging experience, which will keep being interesting and surprising over time, while the meaning *familiar* can be described as 'a friendly relationship based on frequent association', comparable to a favourite jeans that has been worn many times.

The meanings were translated to material properties by analysing them with the MDMS research. In this research, a number of participants was asked to find a material that fits a meaning, to provide an image of it (embodied in a product) and to rate it on a scale of a number of sensorial properties. 13 participants responded for the meaning *intriguing*, and 13 for the meaning *familiar*.

The results of the MDMS research are clustered per meaning in Fig. 3 and Fig. 4. *Intriguing* materials were found to be *surprising* and *unexpected*, by having a different look than feel for instance. They were found to be *playful* and raise curiosity, versatile in their properties and pleasurable to feel. Selected products in which the materials were embodied were practical and functional, but were enhanced by the used material to make them more special and not standard.

Familiar materials were found to be as expected and common. They are considered reliable, and have an air of nostalgia. Most of the selected materials were natural, and recognizable as such. They were embodied in functional, practical products that appeared archetypical for their category.

As seen by the descriptions, certain aspects of the materials are contradicting (e.g. surprising versus expected), and some supplement each other (e.g. warm versus comfortable). Therefore, in some cases it might be possible for the material to be both *familiar* and *intriguing* at the same time, for other aspects it may be necessary to choose for one of the meanings. It is however important to understand how the meanings can be used to enhance and limit each other.

It was decided that the interaction should be *intriguing* at first; by exploring and using the material it will become familiar and personal. This means that the material should be playful, unexpected, raise curiosity and invite to interact with. At the same time, the feeling of the material is important; both for the meanings as for the product category. The feeling of the material should be comfortable, playful and warm, and preferably be recognizable as a natural material. On a performance level, the material should be versatile and reliable, while on a product level it must be practical and functional, with an archetypical shape.

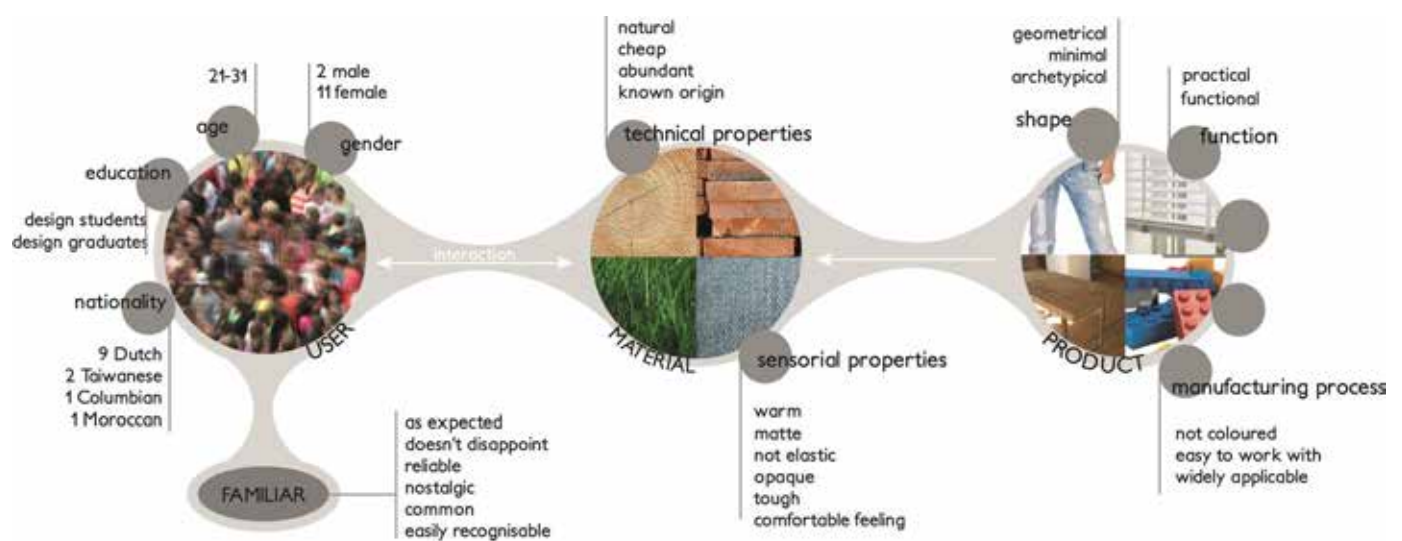


Figure 3. MoM of *familiar* materials

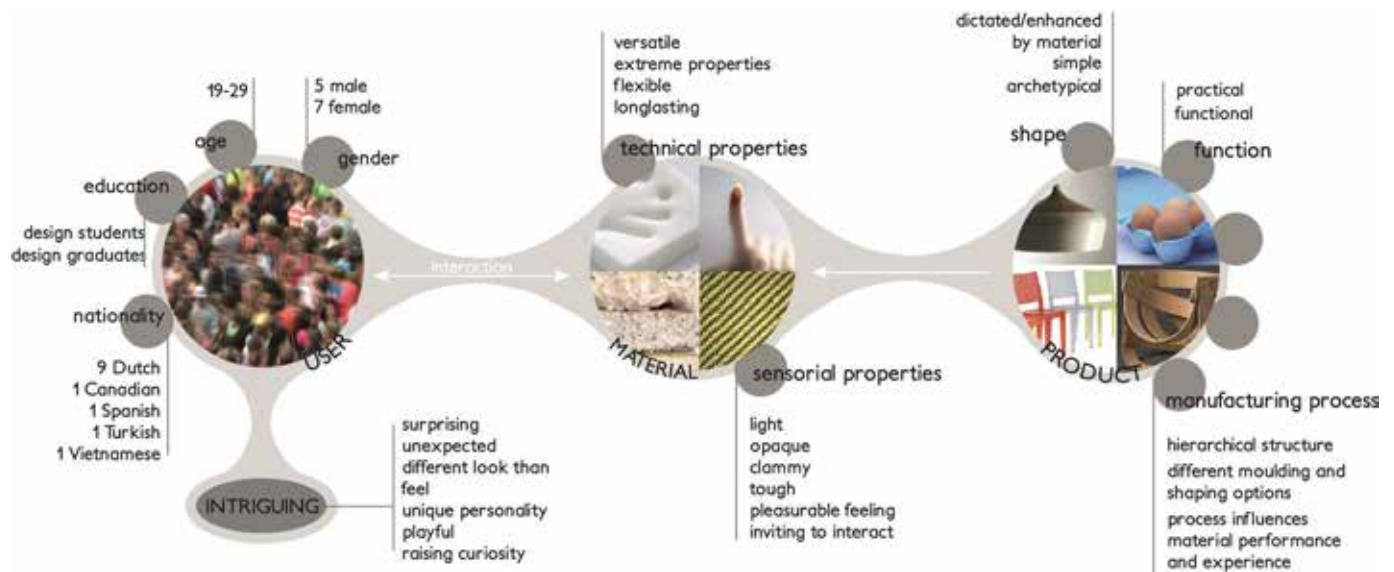


Figure 4. MoM of intriguing materials

3.4. Designing material/product concepts

In the final step, the findings from the previous steps should be used to create material and product concepts. With the material requirements and the findings from the technical and experiential analysis in mind, a number of different MSP samples were created. One MSP seemed to be most promising to be used as a textile-like material, shown in Fig. 5. This was chosen to be used in the product concept creation.

a) MSP development

For the concept creation, two workshops were conducted, one with 13 students of fashion design and one with 12 students of industrial design. The ideas that arose from these workshops were analysed. It was found that the students did not regard the 3D Printed material as a textile; it was rather seen as a substitute for plastic parts that are normally rigid and solid (e.g. casts or braces). This led to the conclusion that for this MSP the structure and process were suitable, but the material was not: although the material (plastic) was familiar, it was not familiar for the context it was intended for. After all, although a lot of textiles are made of plastics, their structure prevents it from being recognized as a plastic.

Therefore, a number of experiments were conducted with different materials. The material that showed the best results and had the best fit with the intended Materials Experience Vision was a mixture of cellulose fibers with a flexible acrylic, as shown in Fig. 6. This mixture can be printed using the AM technology Material Extrusion, in which the material is extruded through a (non-heated) syringe in the desired structure, after which it has to dry. The experiments were performed both by manually extruding the material through a syringe, as well as by mounting the syringe on a material extrusion printer Ultimaker Original. These initial experiments served as a proof of concept for the newly developed material, although more research is necessary in order to make it suitable for processing. However, the results do give an impression of what the material could be like in the future.

b) Product concept

A concept was developed using this MSP. In order to do so, the unique properties of the MSP were analysed: its aesthetics are most prevalent, most notably the pattern that resembles lace and is somewhat prevailing. The structure can be varied with: it can have a square configuration or a hexagonal configuration, changing the appearance and openness of the material. It is also very suitable to make alterations in properties (i.e. making the pattern smaller and higher decreases the flexibility of the material), it makes sense to use it for applications where this quality could be used to the fullest. The product should fit in the category garments, as was part of the assignment. By means of several brainstorm sessions, the most valuable product direction was found to be brassieres. These contain a large number of different parts and functions, therefore they are extremely suitable to locally vary material properties and to integrate parts. The design is shown in Fig. 8. The choice was made to design a corselet, which is essentially a cross between a bra and a top, in order to demonstrate the versatility of the selected MSP.

In the concept, the entire product is 3D Printed exactly to the size of the user and can be custom-made. This means that in theory the exact design can differ, depending on the needs and desires of the user. The design as presented here can be seen as a basis for further adjustments. It is printed at once, meaning there is no need for assembly. This also means that the MSP should fulfill all functions that are usually provided for by a number of different parts and materials.

Two types of the pattern of the material are used: the hexagonal configuration for the cups, in order to accommodate the round shape, and the square configuration for the other parts. In order to provide for the supportive parts, gradients are applied to the material: a gradient in size and a gradient in thickness. Supportive, more structural parts have a smaller pattern size and are thicker (up to 1.5 mm), while the parts that do not have to provide support are thinner (~0.4 mm) and have a larger pattern size, which makes them softer and more pliant.

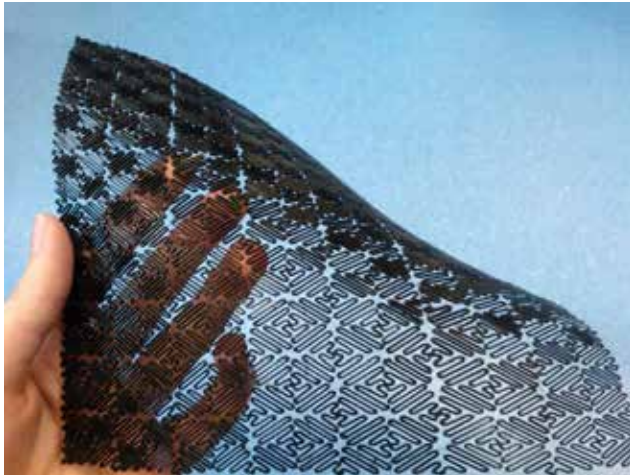


Figure 5. Chosen MSP



Figure 6. Sample of cellulose fibers mixed with flexible acrylic



Figure 7. Prototype of final design

c) Prototype

A prototype of the design was built to test the application of the MSP, as shown in Fig. 7. A dress form was made, to which the product was fitted. It was printed on a material extrusion

printer Ultimaker 2 using the material polylactic acid (PLA), which currently produces the most reliable results on this 3D Printer. It was found that the property gradients in the material worked well, although they could have been a little more pronounced by increasing the z-height. The smoothness of the underside of the MSP increased the skin comfort, although some of the edges were still rather sharp.

d) Life Cycle Analysis

The fact that 3D Printing significantly reduces the number of process steps necessary to produce garments and the amount of waste material, means it has the potential to contribute to environmental sustainability. The total impact of the product was evaluated by means of a Life Cycle Analysis (LCA) (as explained in [16]), and compared to traditional manufactured textiles for 1 kg of textile. It was assumed that the 3D Printed textile was produced by the Fused Deposition Modelling (FDM) process of PLA. The results of the analysis, as shown in Fig. 9, were compared to those of traditional textiles, as analysed in [17]. It was found that the environmental impact of the 3D Printed textile is comparable to those of woven textiles with a yarn thickness of 300 dtex. The largest part of the costs is determined by the FDM process (51%), followed by the costs of the consumer transport by passenger car (31%).

4. DISCUSSION

This paper has shown the application of an MDD method to a design process where AM is the primary production method. The goal of the design project was to create a meaningful application using 3D Printed textiles. Since the method was applied to not only a material, but a combination of material, structure and process, the process was somewhat different. For the first step, it was found that not only an understanding of the material is necessary, but an understanding of the MSP as a whole and of all separate aspects was necessary, including how they influence each other. It was also necessary to research and define the boundaries of the MSP, since this has not been done before.

AM as a primary production process offers the opportunity of creating personalized products, which has influenced the final material concept. Rather than being one fixed material, the material can be locally varied to create property gradients, which results in a range of slightly different materials that all fit the intended vision.

The MSP and product that are created as a result of this process, demonstrate the potential for 3D Printed textiles. Even though the final material does not adhere to all the properties that are desirable for textiles, it has shown potential to be used as a 3D Printed textile for garments. Two main factors that should be improved before it can actually be worn are its tear-resistance and the softness of the material, which is necessary if it is supposed to be worn close to the skin. The latter can be improved by either using a more compressible material or a material with a softer outer surface, such as the proposed cellulose material.

The material as it is designed now is bound by current technological limitations. With improvements of current technologies, some advancements for the material can also be made, it would for instance be interesting to test the behaviour

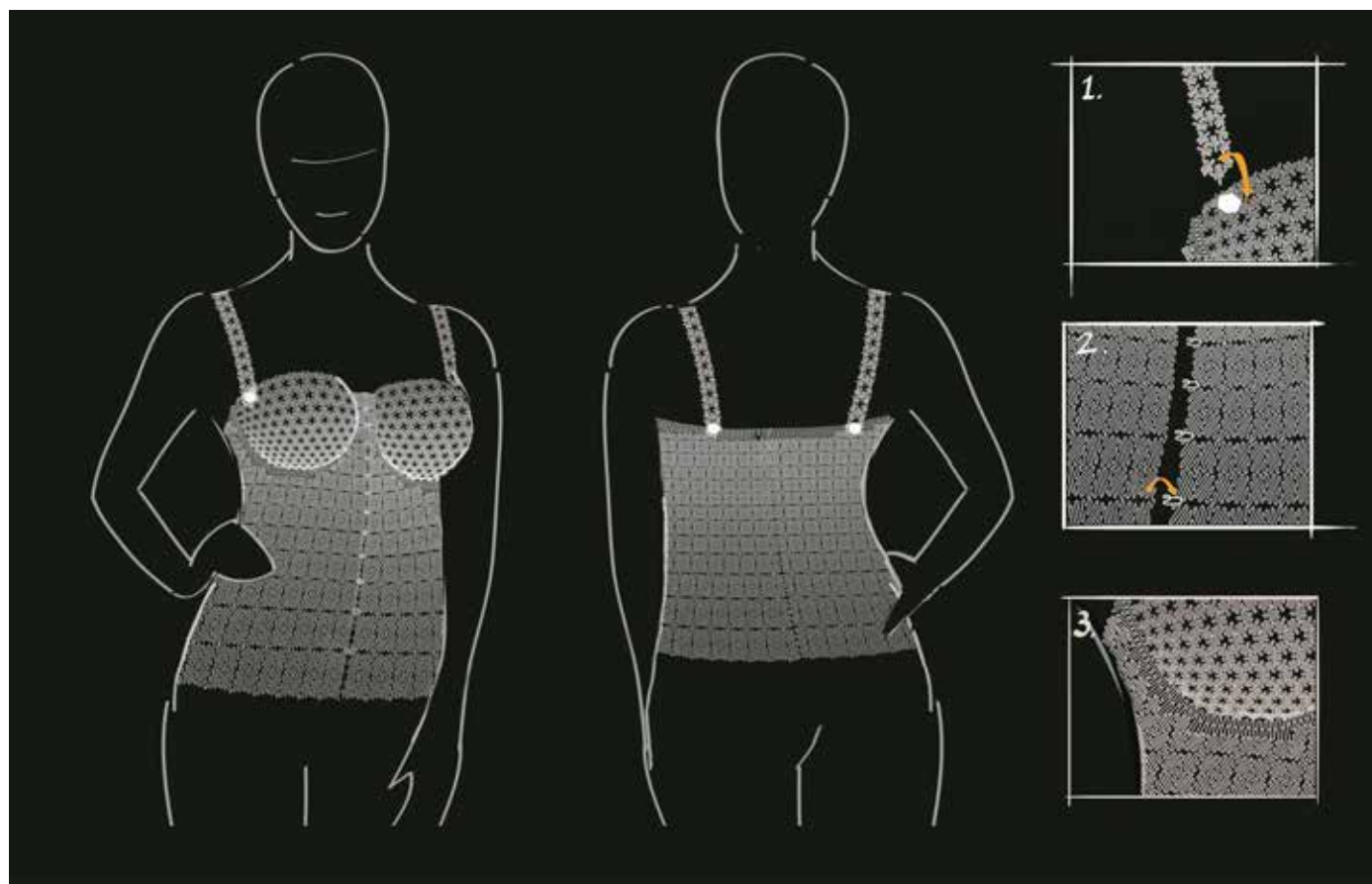


Figure 8. Final design

of the material if the scale of the macro-structure can be decreased, to make it more resemblant of traditional textiles. The current material options were also found to be too limiting, which is why a new material blend was proposed. Although this blend has the potential to be printed, it would be interesting to see different possibilities for printing natural-based materials in the future.

Therefore, for future applications for 3D Printed textiles, it is recommended that an AM process will be developed specifically to create textiles, rather than keep the focus on material development. In essence, textiles should be seen as an MSP: their properties are influenced by materials, structures

and AM processes. In order to be able to print textile-like materials, the materials, structures and process that are in place now should be thoroughly analysed and used as inspiration for new AM processes.

Future work will first be focusing on testing the functionality of the MSP by means of the prototype. Next to that, the cellulose blend will need to be researched further in order to develop it for use in AM and for its function as a textile.

REFERENCES

- [1] J. Kytanen and J. Evenhuis, "Method and device for manufacturing fabric material," WO2003082550 A22003.
- [2] N. Hopkinson, R. Hague, and P. Dickens, *Rapid manufacturing: an industrial revolution for the digital age*. John Wiley & Sons, 2006.
- [3] G. a. Bingham, R. J. M. Hague, C. J. Tuck, a. C. Long, J. J. Crookston, and M. N. Sherburn, "Rapid manufactured textiles," *Int. J. Comput. Integr. Manuf.*, vol. 20, no. 1, pp. 96–105, Jan. 2007.

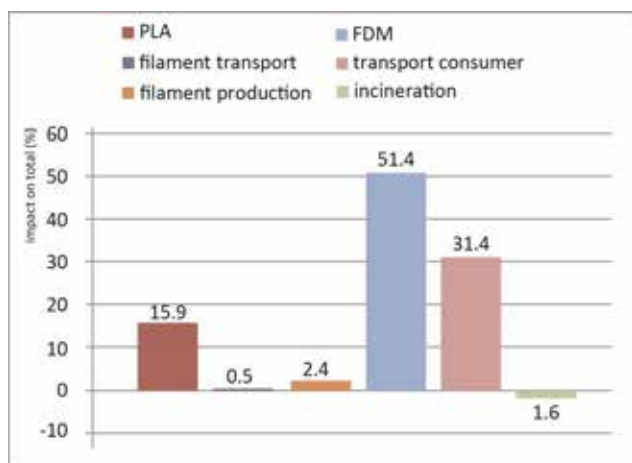


Figure 9. Results of the LCA analysis: impact of each stage of the life cycle of the product as percentage of total impact

- [4] J. J. Crookston, a C. Long, G. a Bingham, and R. J. M. Hague, "Finite-element modelling of mechanical behaviour of rapid manufactured textiles," *Proc. Inst. Mech. Eng. Part L J. Mater. Des. Appl.*, vol. 222, no. 1, pp. 29–36, Jan. 2008.
- [5] A. Johnson, G. a. Bingham, and D. I. Wimpenny, "Additive manufactured textiles for high-performance stab resistant applications," *Rapid Prototyp. J.*, vol. 19, no. 3, pp. 199–207, 2013.
- [6] S. Kivioja, H. Suonsilta, and O. Fi, "Printed material and fabric," pp. 313–321, 2013.
- [7] I. van Herpen, "www.irisvanherpen.nl," 2014. [Online]. Available: www.irisvanherpen.com. [Accessed: 20-Aug-2014].
- [8] E. Karana, B. Barati, V. Rognoli, and A. Zeeuw van der Laan, "Material Driven Design (MDD): An Illustrative Case on Designing With Waste Coffee Grounds."
- [9] E. Karana, P. Hekkert, and P. Kandachar, "A tool for meaning driven materials selection," *Mater. Des.*, vol. 31, no. 6, pp. 2932–2941, Jun. 2010.
- [10] Y. Li, "the Science of Clothing Comfort," *Text. Prog.*, vol. 31, no. 1–2, pp. 1–135, Mar. 2001.
- [11] K. Slater, "Comfort Properties of Textiles," *Text. Prog.*, vol. 9, no. 4, pp. 1–70, Jan. 1977.
- [12] K. Fletcher, *Sustainable Fashion & Textiles: Design Journeys*. London: Earthscan, 2008.
- [13] S. Black, *Eco-chic: the fashion paradox*. London: Black Dog Publishing, 2008, p. 254.
- [14] R. Mugge, H. Schifferstein, and J. Schoormans, "Personalizing product appearance: the effect on product attachment," *Proc. Int. ...*, vol. 31, no. 0, pp. 1–15, 2004.
- [15] E. Karana, "Characterization of 'natural' and 'high-quality' materials to improve perception of bio-plastics," *J. Clean. Prod.*, vol. 37, pp. 316–325, Dec. 2012.
- [16] J. G. Vogtländer, *LCA: a practical guide for students, designers and business managers. Second Edition*. Delft: VSSD, 2012.
- [17] N. M. Van Der Velden, M. K. Patel, and J. G. Vogtländer, "LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane," *Int. J. Life Cycle Assess.*, vol. 19, no. 2, pp. 331–356, Sep. 2014.

Publication 5: Digital design and localised manufacturing P.5

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Redefining the role of designers within an urban community using digital design and localized manufacturing of wearables.

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Abstract— The maker culture has created a dynamic in which designers are less responsible for the design and quality of the final product, but for the tools the consumer uses to create their own.

While additive manufacturing (AM) is gaining acceptance among the general public, it is still seen as a prototyping tool instead of a high quality production technology. This limits its acceptance within co-design and maker culture. The research question is: How to create greater acceptance among the general public regarding the AM technology and its products?

One way to create greater acceptance of digital design and manufacturing is to apply co-design principles on a local scale. By this means the public will be exposed and included in the design and production process, which will ensure the end product is better accepted. In time this could help spark a maker movement within the community. To validate these assumptions a test case was developed in which local design and production of simple wearables, small ready to wear garments like socks or hats, within an urban community will play a major role.

During the research a digital design tool combined with a mobile digital knitting machine was developed to allow for a rapid co-design track. Wearables would be produced by the consumer themselves. The final design of the garment depends on the consumer's choice of material, shape and pattern. A mobile set-up provides the means to test the principle at different locations and allows the consumer to be intensively involved in the maker movement in their own neighbourhood. We implemented a small, low-cost knitting machine that was tested outdoors by park visitors.

The anticipated results for this test case were: increased engagement in the production process, larger acceptance of digital design and an initial maker culture. Although the last result will be difficult to determine as it takes some time to develop. If successful, the maker culture will obtain greater exposure, acceptance and demand for digital design services and products. Even though the maker culture changes the role of the designer will definitely change, their importance to the design process will remain, not as a creator of designs but moreover as a guide to the making of consumer products.

Keywords-component; Co-design, Digital manufacturing, Wearable's, Maker Culture, Sustainability, Local manufacturing

1. GENERAL INTRODUCTION

Even though digital design has made big leaps in the last years, most consumers are still very much unaware of its potential. This is limiting the development as more users and

cases within the field will help mature the technology. In order to facilitate a greater awareness and eventually acceptance we need to look outside the current scope of the exposure of the technology. How to create greater acceptance among the general public regarding the AM technology and its products? This will be the main question addressed in this paper.

There are several means to try and achieve greater acceptance among the general public however, not all are aimed towards this particular issue. When looking at the general knowledge about the production of user products most people are blissfully unaware. This creates a lot of preconceived notions about the difficulties and also possibilities during the production steps. In order to get a more realistic perception regarding AM it is therefore imperative to expose the general public to its difficulties and more importantly its opportunities.

Even though the freedom created by digital design and manufacturing is not necessarily desired by the consumers, it also allows the design community to develop and define this design space through tools and methodology. This ensures that the users of AM facilitated design and production will be able to freely explore its possibilities without being overwhelmed.

The chosen product group, wearables, was selected for its duality. While on one hand garments and other body orientated products are used as an expression of personal style and preference. Yet at the same time it also follows mass consumer behaviour. These two seem to be in direct conflict with each other.

Another aspect in regards to wearables is product fit (Van Der Velden, Patel & Vogtländer, 2014). While no two people are exactly alike the consumers have to cope with standardized sizes. This in stark contrast to the fact that a correctly fitted product can greatly increase the product satisfaction. As such it is an area well suited to the possibilities of digital design and production, as it allows the users to design and wear made to measure or even bespoke tailored garments. Which in turn should result in a greater product attachment which carries value in the field of emotional sustainability.

To ensure that consumers are aware of the possibilities granted by these technologies and expose them to it in a proper way is a challenge. This creates possibilities for designers to reshape their roles within this dynamic. As designers now get the opportunity to create the tools with which the everyday consumer could design and create their own wearables.

To achieve this the following activities were undertaken to test the public's receptiveness to AM produced clothing. First of all a more detailed overview of the developments in local design & manufacturing will be given, as it defines the scope of the research. Followed by selecting a method of creating this acceptance, it will need to fit the context of not just creating acceptance but also instigating a maker spark in the consumer. This will then be applied to an interaction design to create the desired outcome. This interaction will be tested within a public area to validate its effect on the public. After which it will be evaluated and suggestions for adaptations to further improve its effectiveness are given.

2. STATE OF THE ART LOCAL DESIGN & MANUFACTURING

2.1. Redefining the role

Within the current wearables market the interaction is based on the industrial production of clothing. This results in a gap between designer and end user, with producer, wholesalers and retailers as the stakeholders (Figure 1). This construction has benefits, since each stakeholder has a clear task which can be optimized and perfected. However it also results in a lot of global shipping and a gap between designer and end user. The process also relies on large production numbers in order to function creating the need for standardization.

When looking at the new dynamic that is created though local design & manufacturing (LDM) we see that the stakeholders change and that they take on new roles. This contrasting dynamic creates new opportunities and benefits. The close proximity both physically and structurally allows for different design methods and interactions. It creates room for personal/ one off designs as well as small locally influenced series of products. This new dynamic however does ask for different design tools and methods. As such redefining the role of a designer in this context will be imperative. Localized manufacturing has other benefits regarding sustainability, when looking at shipping and emotional sustainability. As the involvement with the creation of the product grows so will the attachment.

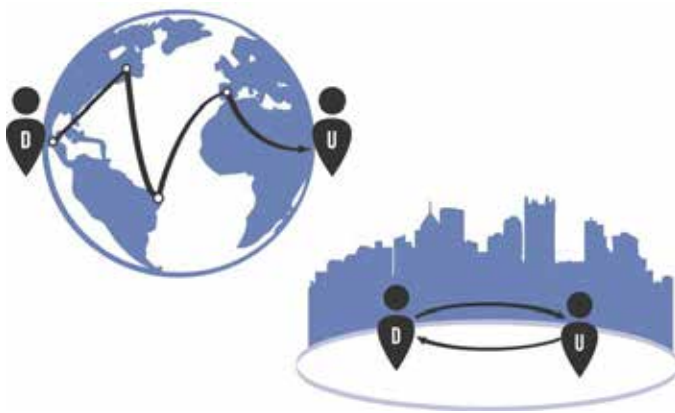


Figure 1. Current interaction and the envisioned interaction between designer and consumer

2.2. Maker culture

One of the main drivers behind localized manufacturing, and a redefining one for designers, is the rise of the maker culture. This cultural shift from mass produced to home-/self-made products is driving a new wave of development in localized manufacturing and design tools and methodology. One of the ways designers can reinvent themselves is to tap into this movement and create the design tools needed for the general public to design and create their own products. While the early adapters have the skills to design and make what they come up with, this will not be the case for everyone. So this leaves a group to design for.

The exposure of this maker culture is something else to consider, the current methods are aimed at the first group. They consist of several facilities/activities:

a) Fablab

The fablab principle is something that fits into the maker culture, as it allows makers to build more complex products for which they do not own the tools or have the expertise to build. These workplaces are stocked with digital manufacturing tools like; 3d printers, CNC machine and laser cutters. These are augmented by the more common tools like; drills, laves and band saws. These spaces are either open to the general public or are linked to educational or artistic institutes. While most major cities around the world have a fablab facility, most are hidden from public view due to location or lack of recognizable markings. This results in a lack of public knowledge about the facilities and as such fails to connect to the general public (<http://fablab.org>).

b) Makerfairs

These events are generally held in public areas/ buildings and generate more public awareness and attention. While still visited mainly by makers, they also attract people generally interested but not (yet) participating in maker culture. These event help to showcase, educate and create appeal for the results of maker culture. This has a great benefit in helping the movement to grow and develop. As fellow makers can meet and exchange ideas. This is augmented by the physical nature of the event in that the products and tools are there and can be used/touched and explored. Still most of the visitors are already interested in or connected to the movement, creating a new wave of makers from yet unengaged people is not the aim of these events. (<http://makerfaire.com/>)

c) Digital Maker Culture

One of the effects of the digital design is the ability to share it using digital media. This does not exclude other non-digital designs as tutorials are also wide spread. This helps to create exposure for the products that can be made. While most users of digital and social media will come into contact with maker culture the effect of seeing a picture or movie is not the same as holding the actual product. This gap between exposure and contact is a limiting factor in creating attraction in regards to the final product (Doctorow, 2009).

3. METHOD

3.1. Co Creation

In order to test the new dynamic between designer and end user it is important to redefine their relation. The freedom created by LDM also creates a larger design space. In order to help guide the end user in this process designers have an opportunity to lend their expertise by means of Co Creation.

Within this design method designers are moving away from translating the needs of the end user into a product. Instead they are facilitating the creation of this product by the end user (Sanders & Stappers, 2008). This shift not only redefines the role of the designer but does the same for the role of the end user. Since They will have a greater influence on the front end of the design process, and as such on the final product

This coincided with the change in dynamic envisioned for the application of LDM as the method allows for local influences to guide the design process. It is not just limited to the local users but also local materials and cultural heritage. This will be used in combination with the design of wearables, were a correct fit and integration of personal style is valuable.

3.2. Concept testing

In order to evaluate the success of a localized manufacturing process concept testing will be used. The concept will be evaluated on several key aspects; general, features, product, durability and reliability. These aspects represent the desired overall qualities of the concept.

By testing the concept using the intended target group as well as the intended context, the following data can be collected photographs, video and interviews. These will show the general public's overall interaction with the concept as well as offer detailed accounts of individual interactions. These results will then be used to create a concept testing matrix. This will either validate or invalidate the concept as a means to achieve the desired goal of creating greater acceptance and interest.

4. DEVELOPING WALLY 120

4.1. Preparations

In order to facilitate the localized manufacturing aspect of the test case, a mobile digital manufacturing tool was needed. In order to use the tool within the local context several criteria where listed:

- It needs to be mobile, or light enough to be moved by a single person (less than 10 kg.)
- Big enough to create small garments; socks, scarfs, hats.
- Self-sustained when in use, no external power needed at the production location.
- Allow for a made to measure approach, allowing the user to take his or her own measurements by adapting an existing template.
- It needs to be reliable, as a minor error will ruin a garment.

- The product coming out of the machine should require little to no extra actions, as close to ready to wear as possible.

In order to create clothing without directly using traditional methods there are several options. There are methods that work with regular yarn and use weaving/knitting techniques. Furthermore 3d printing clothing is being considered within the design community as a replacement of these traditional material and production techniques. However the aim of this research is to test ready to wear garments. While 3d Printing allows for great freedom in shape and construction it is seen more as an haute couture fashion technique for example the works of Iris van Herpen. This combined with the long production time makes it unusable for this research as the aim is to create more acceptance a more intermediate step is needed. As such the following possibilities were taken into consideration. Each will be shortly addressed and checked with the criteria.

a) Knitic, manual knitting machine hack

This system is a recent development, where by hacking the old manual knitting machines you are able to create new digital designs. The Knitic design couple is working with this technology using several interesting input signals to create uniquely patterned designs. The machines are reliable as they basically hack into an existing flat knitting machine.

The main problem this creates is the sheer size and weight of these machines. The machine also is not able to knit full garments as it only allows for sheet knitting, this increases the manual workload after the initial knitting.

Although possibly more reliable they are hard to modify. And while an interesting project it seemed unsuited for the current goal of local exposure.



Figure 2. KNITIC digital design knitting machine & pattern example

b) Circular knitting machine

When looking at the criteria most of the selected garments are tubular in shape. One of the fastest ways to knit in this fashion is using a circular knitting machine. These are very reliable as the knitting motion is never interrupted. They also allow for increasing and decreasing needles, which allows the knitting of heels.

However no progress into digitizing this progress on a small scale has been made at this time. This is also likely related to the fact that sizes are only changeable by switching out the complete needle ring for one with more or less needles.

So while good at what it does it can only do so much. The digital knitters are currently in use on an industrial scale but so far have not been scaled down for personal use.



Figure 3. Circular knitting machine manpowered

c) Openknit

This project was created by Gerard Rubio, as part of his graduation thesis. The OpenKnit system is an open source project working towards creating a digital knitting machine. The designs and software are available for free and together with the bill of materials can be built anywhere in the world. The current design uses 3d printed parts, lasercut parts and some vendor parts. This enables anyone who lives close to a fablabs or has a small workshop at home to reproduce it and contribute to the further development of the device. This opens the project up for wide spread testing and exposure. It works by programming the pattern into Arduino which can be modified to the users specifications.

The machine however is bulky and in its early stages of development. It also has some issues regarding reliability. The machine does offer the freedom to create several different types of garments. Currently ranging from dresses to sweaters to beanies. While not ready for complex patterns it does allow for different colours.



Figure 4. OpenKnit, open source knitting machine

4.2. Developing a mobile solution

The OpenKnit system was selected as it offers a combination of open/digital design combined with an open source machine. This allows end users or communities to create their own machine while also allowing the designers to adapt them to their specific needs. However the current design of the OpenKnit system was not suited for mobile use, several adaptations would have to be made.

Therefore the machine was redesigned to be smaller, lighter and sturdier. Several tests were executed to test the new components durability and reliability, this was done on the main machine. The main components were all tested and (partially) redesigned. This was mainly focused on the carriage and the rack & pinion. The carriage is responsible for both guiding the thread as well as controlling the motion of the needles. Where the rack & pinion is vital to the accuracy of the machine as it creates the input for the software to determine the carriage position on the needlebed.

The resulting machine was mountable on any flat surface using two clamps, weight was reduced to 5,5 kg. Its needle beds have a total of 120 needles, 60 a side. This is sufficient to produce a small wearables. It is battery operated using a 12v battery and converter circuit to power both the stepper motor and servo's which run on 12 and 5 volts respectively.

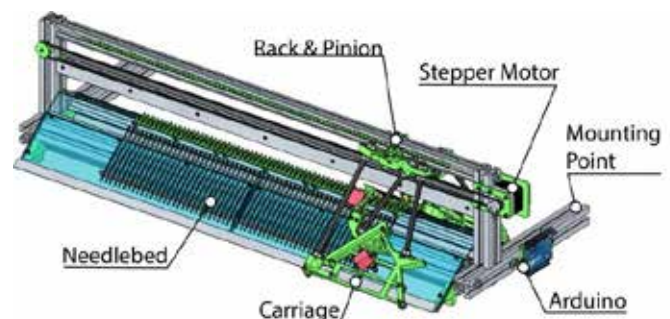


Figure 5. The redesigned OpenKnit machine "wally 120" also shown are the main components if the machine

5. ENGAGING LOCAL COMMUNITY

5.1. Test set-up

When selecting the type of garment to make it was decided to make a beanie. This simple woolen cap design would allow for a quick turnaround during the sessions and would allow the machine to run without interruption for a long period of time without spending too much time on the production of the garment. In total it takes 35 minutes to create.

The following set-up was used, it follows the shown scenario. The test scenario consists of several steps each with their own function. The first step is to set-up the machine on its location, this means attaching the machine to a supporting structure. This can be a structure available on site or one that is brought. Attaching Wally is done with clamps, which ensures a solid connection without damaging the structure. The second step is to hook up the electronics, this consists of connecting the battery and the USB cable to the laptop. For the third step an interested onlooker is approached, a short explanation is given about the purpose of the machine and the general theory. If the person is interested a short production track can be started. This started with the fourth step here we measure the size of the head in order to make a beanie made to measure. This data will be insert into the Arduino software upon which the needlebed is prepared. The fifth step is threading the machine and setting up the first two lines manually. Afterwards the Wally takes over and knits the garment to its desired length. An optional step is to cut and splice a different colour thread during the knitting process. For the last step the garment is closed manually while still on the machine and then removed from the comb and needlebed. It is then ready to wear (Figure 6).

During the knitting of the wearable and afterwards, the users are asked to express the experience and they are given the opportunity to ask any questions they might have.

Secondly they are asked to share their expectations and desires regarding the machine and its applications. This ranges from what they would use it for themselves, to what they would eventually want to be able to make with it. This will

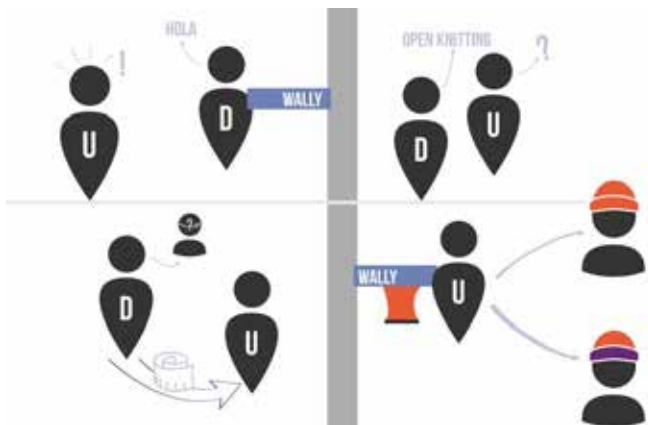


Figure 6. The Test scenario

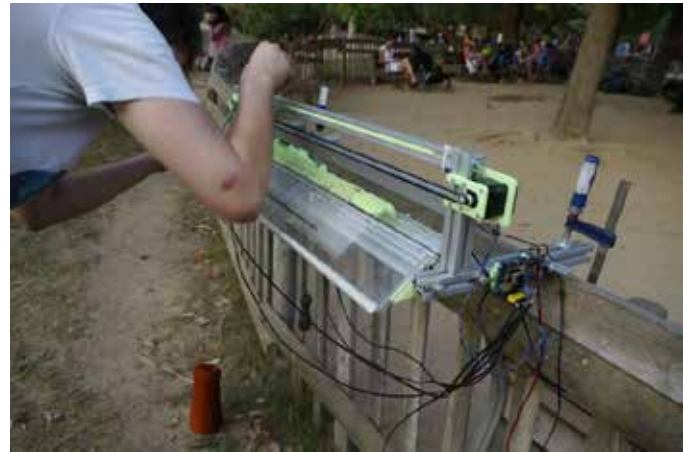


Figure 7. The set-up

give an insight into their standings in relation to the technology and might also illustrate the changes herein, as a result of this new experience.

The sessions will be documented by both video and camera footage. This will later be used to analyse the effect of this new interaction that occurs within the public space. Important is to also document the range of interactions and steps the public goes through.

5.2. Test location

In order to get enough exposure the test location is of significance. While the centre of Barcelona is lively and full of people, the tourist is not the target audience. While people are very open to new things while on vacation the main goal of the test is to see if the general public is willing to accept AM technology and maker culture. To this end the Parc de la Ciutadella was selected, this city park is visited mainly by the local population. The park is still crowded enough to have enough exposure while not including too many tourists into the test group.

The mounting of the machine did limit the selection of the test site as most of the surfaces were unfortunately rounded and therefore unsuited for the chosen mounting system. The chosen site was located near a intersection of the walkways and the playground (Figure 7). Especially the proximity to children was useful as their curiosity and lack of inhibitions will help pull in more people.

5.3. Results

The results of the test session held in the Parc de la Ciutadella, show a great variety of interest. The session created a good crowd of people looking at the machine at work. The steps described in 4.2 were followed as closely as possible as the installation would allow (Figure 8). As expected the children were first to explore, drawing in their parents and later more bystanders joined to see what was going on. As can be seen in Figure 9 the public was rather mesmerised by the machine. The movement and sound creating interest and upon closer inspection questions start to arise about the project, the overall goals and future use.

Ranging from remarks about the look of the machine to the technical specifications used to create it. This wide range of interest was already very useful. The wonderment seemed to suggest that most people had never seen a machine like this in action, not to mention in the middle of a public park.



Figure 8. Testing the machine (top) measuring the size,(middle) knitting the beanie, (bottom) ready to wear



Figure 9. Some of the gathered audience

The answers to the questions were mixed and varied wildly in detail so in order to get a quantitative overview they were categorized as positive, negative or indifferent. This creates the following overview in regards to the questions, as seen in Figure 10. In total 26 people took the questionnaire during the session. The questions focused on the following aspects of the concept: general impression, available features, reliability of the machine, functionality of the product and the durability of the machine.

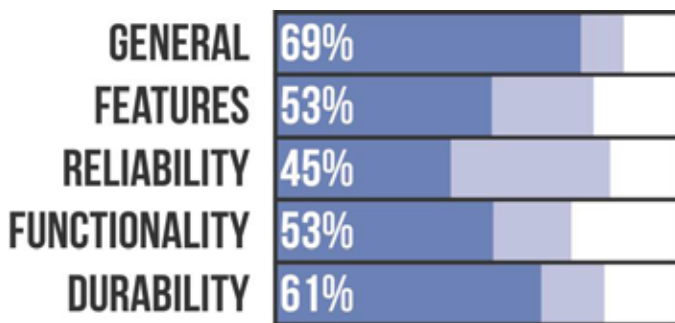


Figure 10. Quantitative overview of the questionnaire positive/negative/indifferent

When discussing their possible future use of this technology, the responses were categorized as well. This question was aimed to determine the likelihood they would use this machine or something similar in the future. The responses ranged from; definitely, possibly & never. This resulted in the following overview:



Figure 11. Possibility of future use definitely/possibly/never

With regards to the type of desired use the following categories were given: small wearables/ Simple sweaters, dresses & vests/ Hoodies, buttoned & other complex garments. This was to see what type of garment they want to create should they use the machine themselves. They were told to ignore size or current technological limitations in this answer. The results were as followed:



Figure 12. Percentages off desired use for Small/Simple/Complex garments

When asked why they would use the machine instead of buying readymade garments their response were mainly focused around the following properties; better fitting clothes (72%), more freedom in creation/personal style (45%) and

lower price (30%). This was in within the context of made to measure patterns. Were they can enter their measurements and select patterns/colours freely.

6. DISCUSSION

When looking at the results of the engaging local community test case seems to check all the boxes in regards to the successful realisation of greater acceptance. However when looking at the test set-up and general several issues came to light.

First, the test location in combination with the time the test was held at. The test was carried out during the late afternoon early evening 18:00 -20:15. This might have an effect on the results in that the public could be tired, on their way home. In order to exclude these and other factors from the results a second session at a different location and time of day would be needed.

Secondly, while the machine performed well it struggled due to the method of placement. The gate it was attached to resulted in an off level position which created a greater strain on the system then initially anticipated. In order to prevent this in future tests either the mounting system or mounting location will need to be addressed. As the struggling machine has effect on the perception of durability and reliability as mentioned by one of the participants; "It seems to struggle a lot, especially going towards the edges of the beanie, does it always do this?". In order to create a positive image for AM technologies the reliability will need to be increased.

Another effect of the Wally 120 system that limits the testing at this point is the lack of interface design integrated into the system. In order to let the public use the machine by themselves, an interface will need to be developed. This also ties into the limitations currently attached to the machine as it is still not able to decrease needles, needed to be able to do short stitching. This is still under development and once completed will greatly increase the range of designs the Wally 120 could handle.

Also there was the matter of language. Even though a Spanish native was present during the testing the researcher himself did not speak Spanish this created some difficulties explaining the machine and answering the questions. While this did not affect the general insights into the effect of the machine it did limit detailed discussions.

7. CONCLUSIONS

The concept of introducing a localized manufacturing tool into an urban community resulted in a positive response from the general public. When looking at the results it is clear that when confronted with AM technologies in a urban context general interest is increased.

Looking at the Attention Interest Desire Action or AIDA model the following can be concluded. The Attention was created, the Wally drew in a large crowd before it was even turned on. The Wally was considered intriguing, because of the colour, sound and overall shape that stood in stark contrast with its surroundings.

Attentiveness was high, 70% of the people that stopped to take a longer look asked questions, made pictures or were talking amongst themselves about the machine. When looking at the answers in regards to future use the crowd was positive. 64% of the participants of the questionnaire would use this machine if it would function similarly to the test conditions.

53% of the participants would use the machine for complex garments, while 87% of them would use it for small simple garments. This shows significant interest and desire in regards to using the machine.

Action was not addressed in this test as the machine is still in development. However the initial responses regarding the Wally 120 were positive and several machines are currently under construction around the world.

A important thing to notice is their need for better fitting clothes as 72% of the participants claim this as a reason to start using this type of clothing manufacturing. It seems that even though the standardisation of clothing is able to facilitate the industrial production of clothing it does not seem to fill the needs of the users.

When looking at the role of the designer in this process, it can be concluded that this has been altered. The designer is no longer just creating products that fill the needs of the consumers. Instead we see a new task taking shape, designing and defining the tools and design space for the end user. This is partially done with a co creation process at this time. However this can be further developed to let the users freely design and manufacture their products without any direct contact. The contact between user and designer will then be through the design space created by the designer.

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Thanks also go out to the people at Arduino. There financial support to the OpenKnit project enabled to the fast creation of the Wally 120 machine. And allowed Cees Jan to prolong his stay in Barcelona further improving on the OpenKnit project in general.

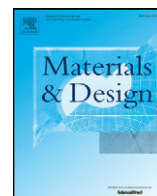
9. REFERENCES

- [1] Elizabeth B.-N. Sanders & Pieter Jan Stappers (2008) Co-creation and the new landscapes of design, *CoDesign: International Journal of CoCreation in Design and the Arts*, 4:1, 5-18
- [2] Johansson, A., Kisch, P., & Mirata, M. (2005). Distributed economies—a new engine for innovation. *Journal of Cleaner Production*, 13(10), 971-979.
- [3] Moore, W. L. (1982). Concept testing. *Journal of Business Research*, 10(3), 279-294.
- [4] Page, A. L., & Rosenbaum, H. F. (1992). Developing an effective concept testing program for consumer durables. *Journal of Product innovation management*, 9(4), 267-277.
- [5] Guljajeva, V. & Canet M. (2013, March 21). Knitic demo & tutorials now online!. Message posted to <http://www.knitic.com/>
- [6] OpenKnit. (2014). Made In the Neighbourhood (ft. a clothing printer, OpenKnit) Retrieved March 8, 2014 from: <http://vimeo.com/86987828>
- [7] Elissa, K., 2004, 'Title of paper if known'. Paper presented at the conference, place, unpublished.
- [8] Van Der Velden, N. M., Patel, M. K., & Vogtländer, J. G. (2014). LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane. *The International Journal of Life Cycle Assessment*, 19(2), 331–356. doi:10.1007/s11367-013-0626-9
- [9] E.K. Strong (1925) Theories of Selling *Journal of Applied Psychology*, volume 9, pagina 75-86
- [10] Doctorow, C. (2009) *Makers*. New York City, NY: Tor Book

Publication 6: LCA and ecodesign of smart textiles

P.6

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



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ABSTRACT

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

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

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

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1. Introduction

1.1. Background and hypothesis

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

The above developments have led to an enormous variety of smart textile prototypes that have been presented at fairs and exhibitions. The textile sector embraces these innovative ideas as they offer plenty of possibilities for novel products and open up new business opportunities for the textiles and fashion industry [43,50]. Innovations in smart textiles technology promise to add value to the consumer's life and satisfy the textile industry's demand for new market opportunities. Previous innovation cycles, and this concerns the high-tech sector in particular, showed how novel technologies unexpectedly proliferated the daily life of average

consumers within a relatively short time. Examples of break-through applications encompass digital watches, mp3-players, smart phones, and tablet PCs. Smart textiles have a potential to become the next item in that row and observers of the smart textile innovation process forecast the technology to proliferate at the consumer market within a decade and become an integral part of future life styles in future.

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

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

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

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

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

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

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

1.2. E-textiles and the environment

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

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

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

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

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

1.3. LCA and eco-design of e-textiles

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

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

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

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

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

2. Method

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

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

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

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

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

3. Case-study of Vibe-ing

3.1. Introduction

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

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

3.2. The prototype

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

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

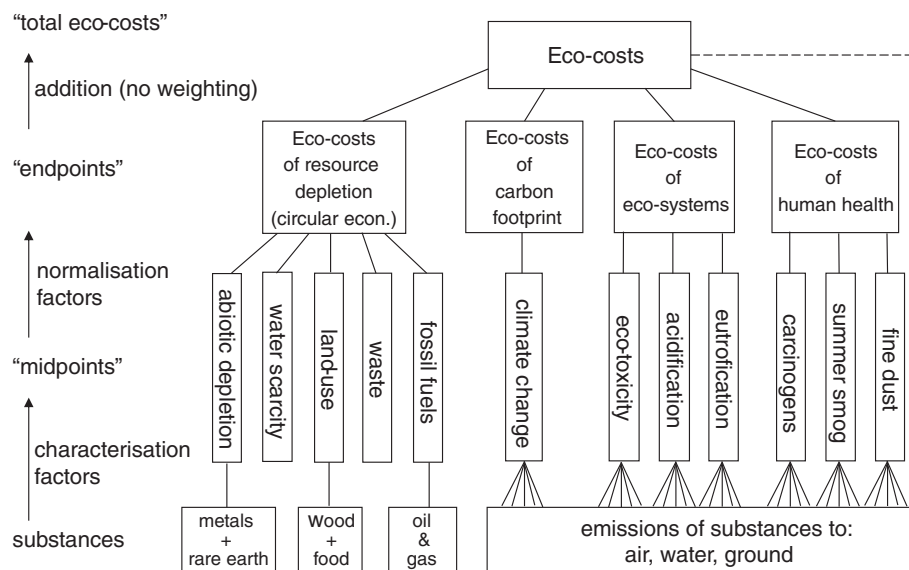


Fig. 1. The structure of the system of the eco-costs.



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

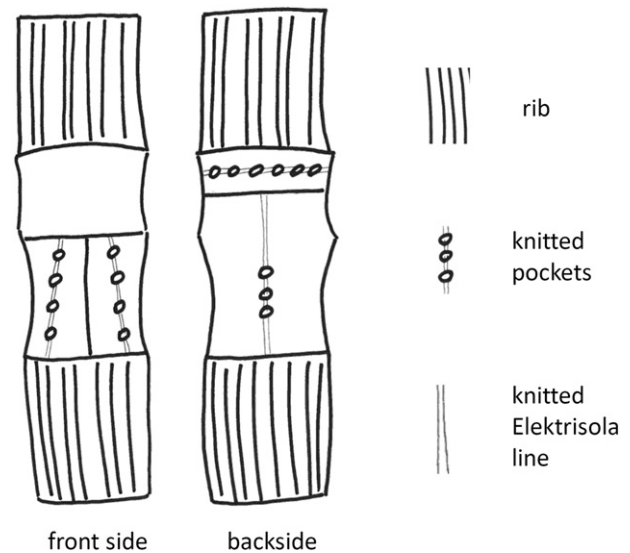


Fig. 3. Illustrative technical drawing of the complete Vibe-ing.

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

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

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

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

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

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



Fig. 4. Knitted pockets.

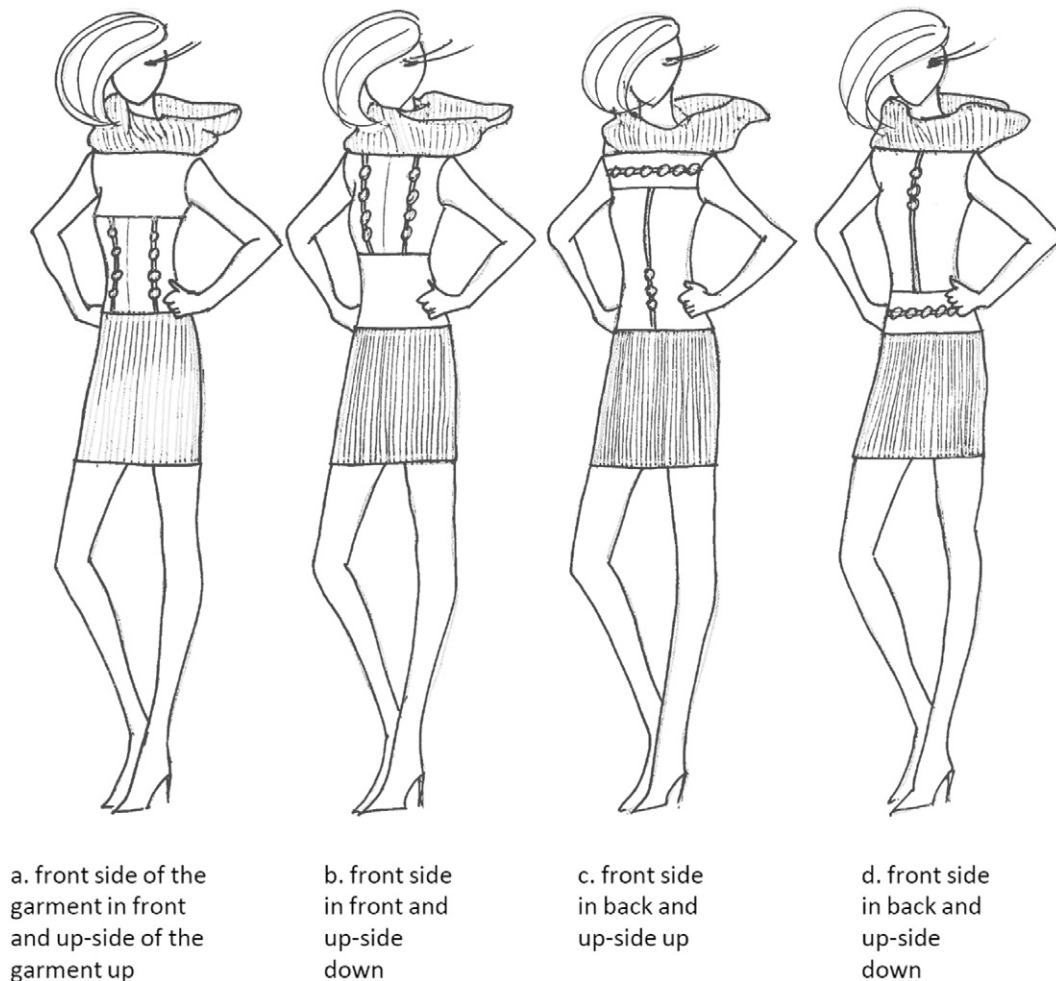


Fig. 5. a–d. Illustrative drawings of Vibe-ing, showing the four ways it can be worn by the wearer, to stimulate different areas of the body.

3.3. Life cycle assessment of Vibe-ing

3.3.1. Goal and scope

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

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

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

3.3.2. Inventory analysis

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

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

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

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

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

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

3.3.3. Impact assessment results

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

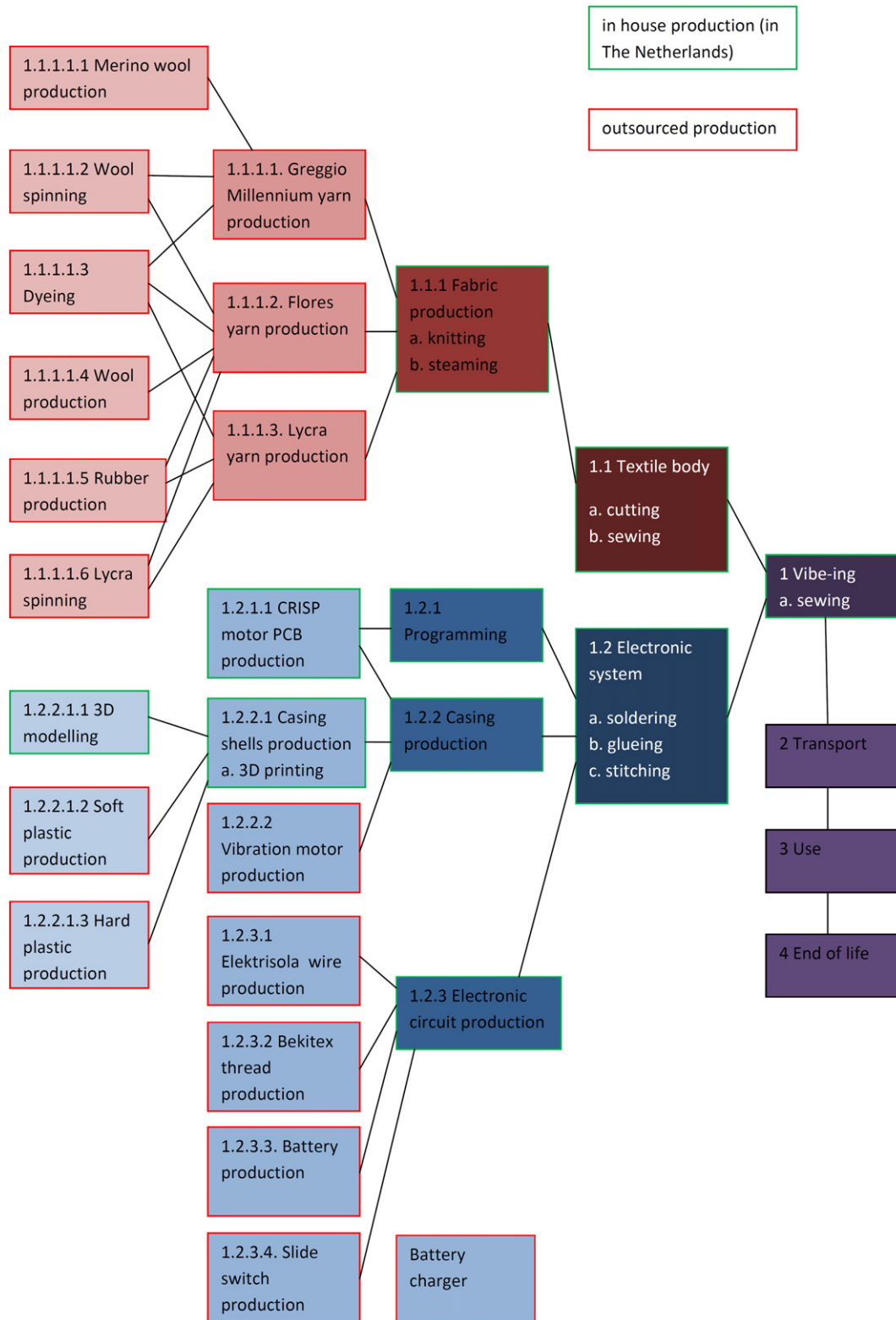


Fig. 6. Process tree diagram of Vibe-ing.

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

Fig. 9a–d presents the detailed environmental impact of the Vibe-ing production phase. Fig. 9a shows the eco-costs for the electronic system and Fig. 9b the division over the Electronic circuit of which the impact is completely caused by the production of the Elektrisola yarn. Fig. 9c

presents the breakdown over the textile body and Fig. 9d the division over the production phase of the material with the biggest impact, namely the Greggio Millennium yarn production.

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

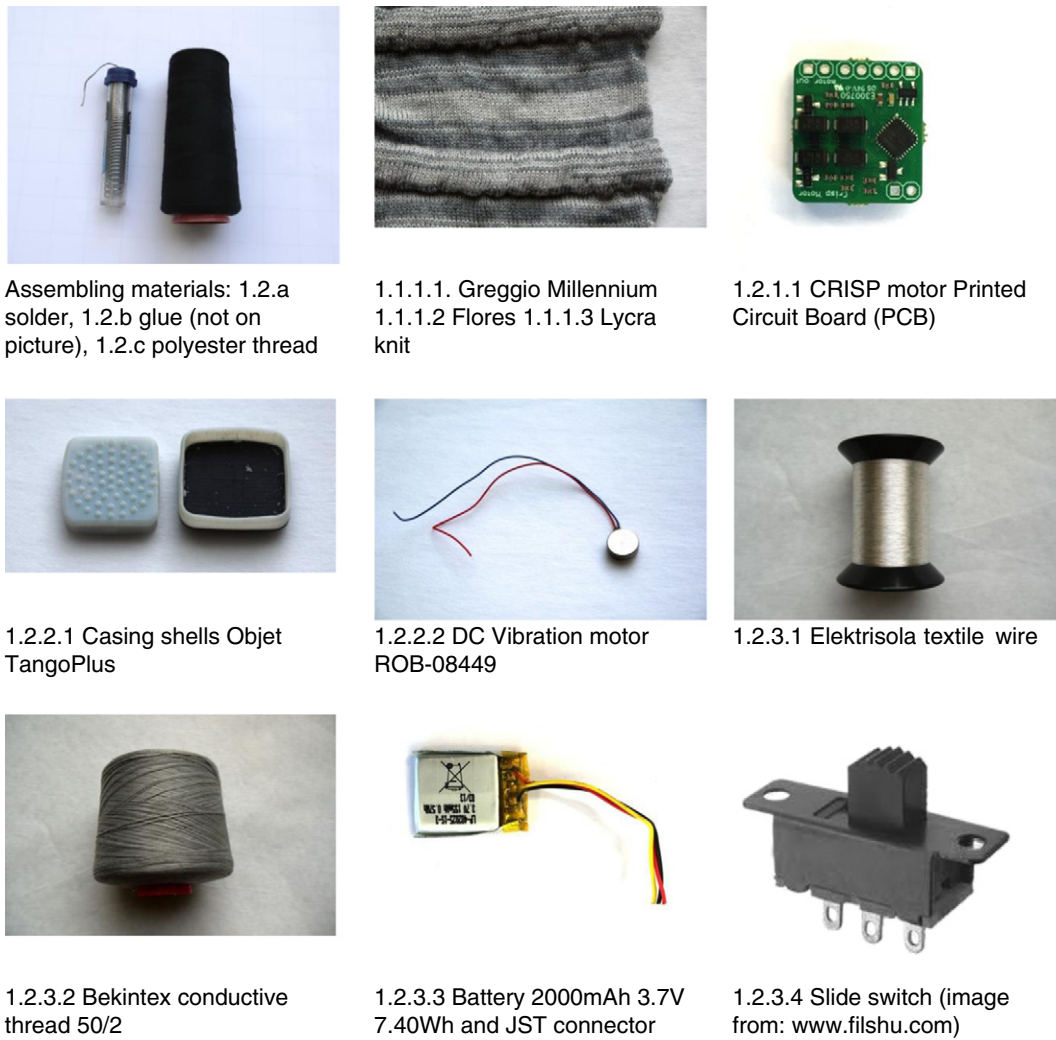


Fig. 7. Photos of the textile and electronic materials used in Vibe-ing.

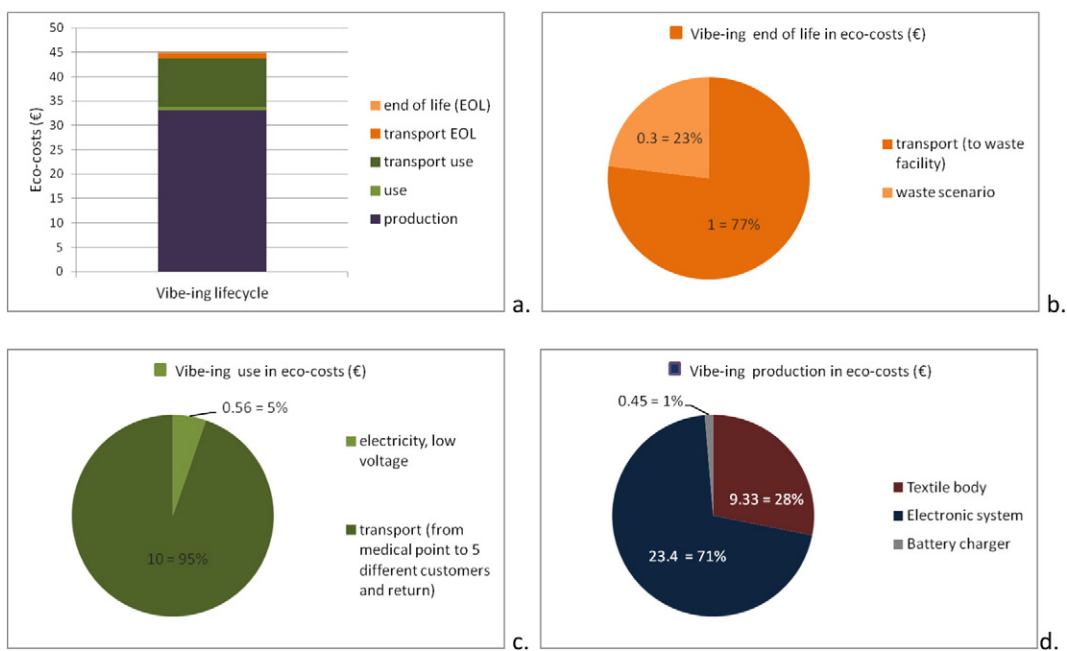


Fig. 8. a–d. LCA results over the Vibe-ing life-cycle per life cycle phase.

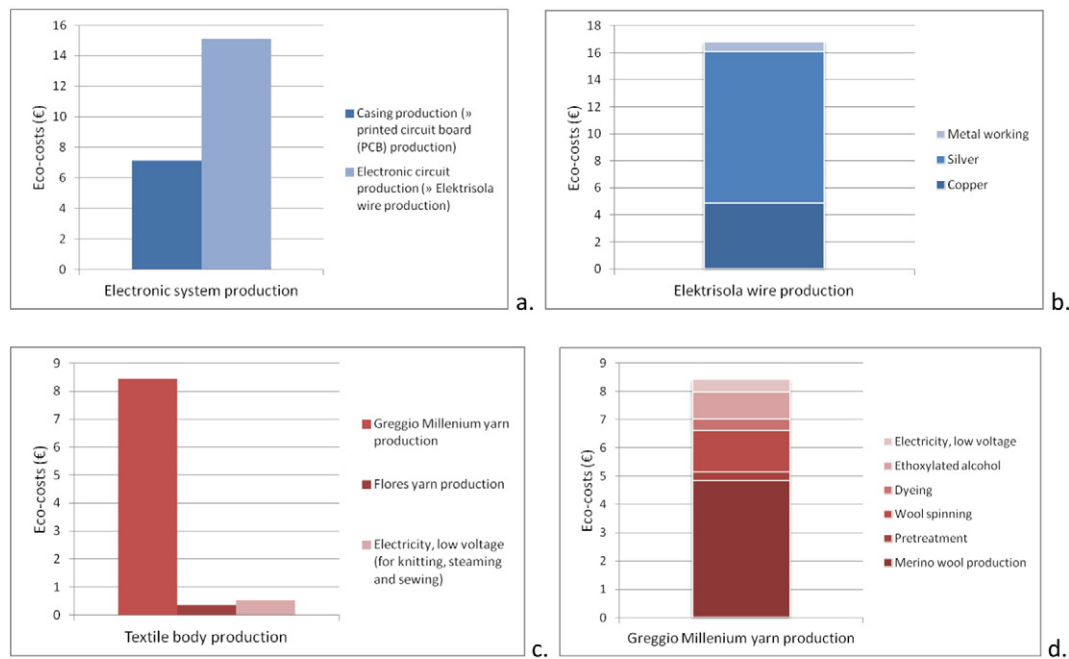


Fig. 9. a–d. Environmental impact of the Vibe-ing production phase.

Calculations for the environmental impact in three other frequently used indicators – namely: CO₂ equivalent (CO₂ eq.), Cumulative Energy Demand (CED) and ReCiPe (H/A weighting) – were made as well. However, these did not yield satisfactory results because not all of these indicators include all impact categories – such as human toxicity, eco-toxicity, materials depletion and land use. These data are available though and can be provided upon request.

3.3.4. Interpretation

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

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

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

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

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

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

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

3.4. Eco-design of Vibe-ing

3.4.1. Selection of eco-design strategies

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

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

3.4.2. Eco-redesign options

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

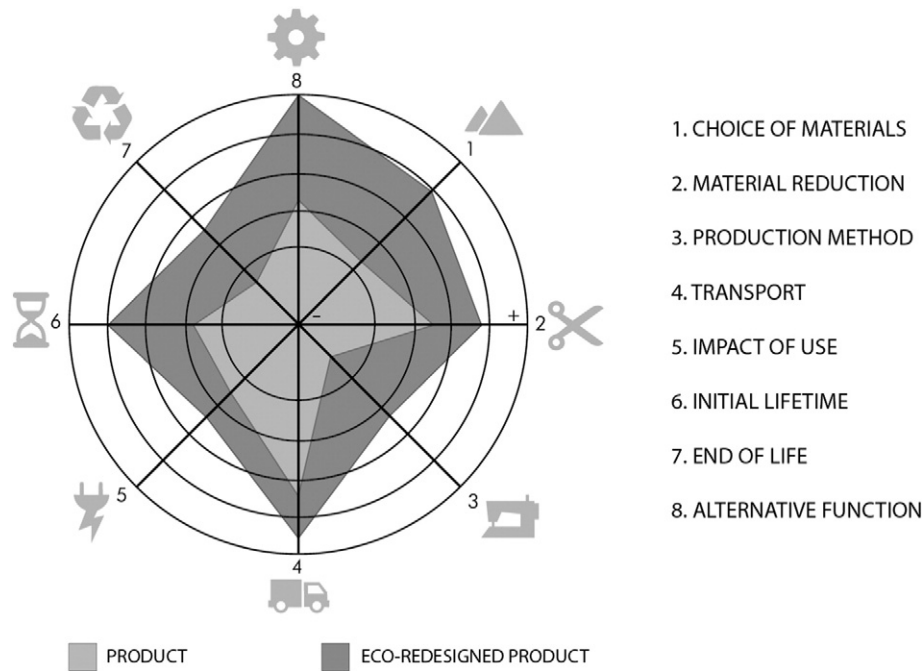


Fig. 10. The Eco-design Strategy Wheel, graphical reproduction designed by K.M. Lussenburg.

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

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

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

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

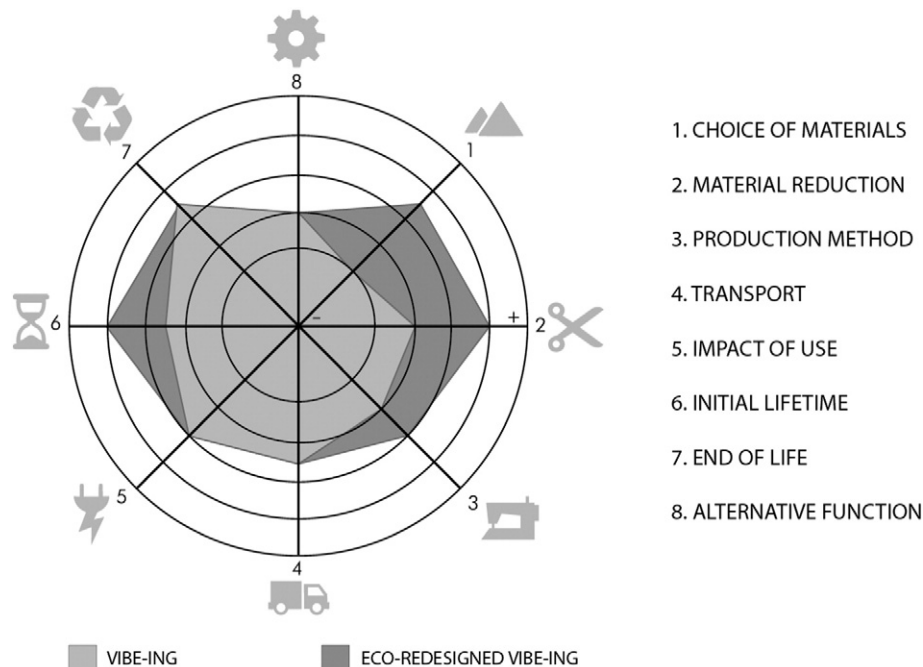


Fig. 11. Eco-design Strategy Wheel with the Vibe-ing and the eco-redesigned Vibe-ing.

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

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

Electr. = electronic.

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

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

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

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

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

Eco-design strategy 3 is about the production methods. In first instance it was expected that the 3D printing of the casings would have a substantial influence, but the LCA base-case calculations do not confirm this. Although the knitting process itself does not have a large influence (the impact of the electricity use of this process is minor, see Fig. 8c.), the choice of the designers to apply the specific jacquard knitting technique has significant consequences for the amount of material to be used. Jacquard knitting creates a voluminous and comfortable structure, but consumes additional material (and energy) because –

in simple words – the knitting movement is executed twice. By choosing another – more simple – knitting method it is estimated that 50% of the knitting material can be saved which gives a reduction of more than (because for this rule of thumb calculation the energy savings and the material savings of the electronic materials are not taken into account) 45% of the impact of the textile body and more than 14% of the assembly. Since for this redesign the surface of the dress remains similar to the original, the secondary effect because of extra ambient heating (as for redesign 2b) is expected not to take place. The difference with the Vibe-ing prototype will mainly be that the body-material will be thinner, which will have an effect on the feeling of wearing but it is expected that the thinner material will be enough to give the body the necessary warmth for the treatment.

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

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

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

4. Discussion and conclusions

From the market perspective smart textiles have not yet spread into everyday casual wear. Since e-textiles are set to proliferate the

worldwide ‘fast fashion’ apparel sector in future, all environmental aspects related to the complete life cycle must be taken into account already in the design stage. For now we can already discuss the prospective environmental problems around e-textiles in an early stage of innovation. In this discussion, the possibility that the development of smart textiles – whether or not in combination with service systems – could lead to sustainable products and – product service systems (PSS), should be included [28].

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

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

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

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

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

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References

- [1] C. Bakker, M. Den Hollander, E. Van Hinte, Y. Zijlstra, Products That Last. Product Design for Circular Business Models, TU Delft Library, 2014.
- [2] A. Barber, G. Pellow, LCA: New Zealand merino wool total energy use, 5th Australian Life Cycle Assessment Society (ALCAS) Conference, 22–24 November 2006, Melbourne, Australia, 2006.
- [3] H. Brezet, Dynamics in eco-design practice, *Ind. Environ.* 20 (1–2) (1997) 21–24.
- [4] H. Brezet, C. Van Hemel, Eco-design: a promising approach to sustainable production and consumption, in: H. Böttcher, R. Clarke (Eds.), *Industry and Environment*, United Nations Environment Programme, Paris, France, 1997.
- [5] CRISP, www.crispplatform.nl2014 (accessed on 10-09-2014).
- [6] J. Cheng, P. Lukowicz, N. Henze, A. Schmidt, O. Amft, G. Salvatore, G. Troster, Smart textiles: from niche to mainstream, *IEEE Pervasive Comput.* (3) (2013) 81–84.
- [7] K. Cherenack, L. van Pieterse, Smart textiles: challenges and opportunities, *J. Appl. Phys.* 112 (9) (2012) 091301.
- [8] G. Cho, S. Lee, J. Cho, Review and reappraisal of smart clothing, *Int. J. Hum. Comput. Interact.* 25 (6) (2009) 582–617.
- [9] Eco-invent, Database Ecoinvent Version V3.01, The Swiss Centre for Life Cycle Inventories, 2014.
- [10] EN ISO 14006, Environmental Management Systems – Guidelines for Incorporating Eco-design, Brussels, 2011.
- [11] J.R. Ehrenfeld, The importance of LCAs – warts and all, *J. Ind. Ecol.* 1 (2) (1997) 41–49.
- [12] EU Eco-design Directive, <http://www.eceee.org/eco-design2014> (accessed on 29-10-2014).
- [13] EVR, The Model of the Eco-costs/Value Ratio (EVR), <http://www.ecocostsvalue.com/index.html>2015 (accessed on 15-04-2015).
- [14] J.B. Guinée, Handbook on life cycle assessment – operational guide to the ISO standards, *Int. J. Life Cycle Assess.* 7 (5) (2002) 311–312.
- [15] Idemat, Database Idemat Version V. 2014, Delft University of Technology, 2014. (Available at <http://www.ecocostsvalue.com/EVR/model/theory/subject/5-data.html>).
- [16] ISO 14040, Environmental Management – Life Cycle Assessment – Principles and Framework (ISO 14040:2006), 2nd edn ISO, Geneva, 2006.
- [17] ISO 14044, Environmental Management – Life Cycle Assessment – Requirements and Guidelines (ISO 14044:2006), ISO, Geneva, 2006.
- [18] R.K. Kanth, Q. Wan, H. Kumar, P. Liljeberg, L. Zheng, H. Tenhunen, Life cycle assessment of printed antenna: comparative analysis and environmental impacts evaluation, *Proceedings of the 2011 IEEE International Symposium on Sustainable Systems and Technology (ISSST)*, 1 2011, p. 1.
- [19] E. Karana, Characterization of ‘natural’ and ‘high-quality’ materials to improve perception of bio-plastics, *J. Clean. Prod.* 37 (2012) 316–325.
- [20] E. Karana, P. Hekkert, P. Kandachar, Materials experience: descriptive categories in material appraisals, *The International Conference on Tools and Methods in Competitive Engineering (TMCE)*, Izmir, Turkey, 2008.
- [21] E. Karana, N. Nijkamp, Fiberness, reflectiveness and roughness in the characterization of natural and high quality materials, *J. Clean. Prod.* 68 (2014) 252–260.
- [22] E. Karana, O. Pedgley, V. Rognoli, Materials Experience: fundamentals of materials and design, Butterworth-Heinemann, 2014.
- [23] E. Karana, O. Pedgley, V. Rognoli, On Materials Experience, *Design Issues* 31 (3) (2015) 2015 [Summer].
- [24] W. Klöpffer, Life-cycle based methods for sustainable product development, *Int. J. Life Cycle Assess.* 8 (3) (2003) 157–159.
- [25] A.R. Köhler, Challenges for eco-design of emerging technologies: the case of electronic textiles, *Mater. Des.* 51 (2013) 51–60.
- [26] A.R. Köhler, L.M. Hilty, C. Bakker, Prospective impacts of electronic textiles on recycling and disposal, *J. Ind. Ecol.* 15 (2011) 496–511.
- [27] A.R. Köhler, C. Lauterbach, A. Steinhage, J.C. Buitier, A. Techmer, Life cycle assessment and eco-design of a textile-based large-area sensor system, *Electronics Goes Green 2012 +, ECG 2012 – Joint International Conference and Exhibition, Proceedings* 6360445, 2012.
- [28] K. Kuusk, K. Niinimäki, S. Wensveen, O. Tomico, Smart textile products and services in sustainability context, *Ambience’14&10i3m*, 7–9 September 2014, Tampere, Finland, 2014.
- [29] S. Lam Po Tang, G.K. Stylios, An overview of smart technologies for clothing design and engineering, *Int. J. Cloth. Sci. Technol.* 18 (2) (2006) 108–128.
- [30] S.E. Laursen, J. Hansen, H.H. Knudsen, H. Wenzel, H.F. Larsen, F.M. Kristensen, EDIPTX – Environmental Assessment of Textiles, Danish Environmental Protection Agency, 2007.
- [31] LCAtogo, Technical Report on Needs and Demands of SMEs, www.lca2go.eu2013 (accessed on 28-02-2014).
- [32] L. Li, W.M. Au, T. Hua, D. Feng, Smart textiles: a design approach for garments using conductive fabrics, *Des. J.* 17 (1) (2014) 137–154.
- [33] J.P. Malins, J. Steed, S.M. Fairburn, S. Robertson, L. McIntyre, L. Cruickshank, K. Scott, Future Textile Visions: Smart Textiles for Health and Wellness, Robert Gordon University, Aberdeen, 2012.
- [34] A. Mestre, J. Vogtlander, Eco-efficient value creation of cork products: an LCA-based method for design intervention, *J. Clean. Prod.* 57 (2013) 101–114.
- [35] N. Mirabella, V. Castellani, S. Serenella, LCA for assessing environmental benefit of eco-design strategies and forest wood short supply chain: a furniture case study, *Int. J. Life Cycle Assess.* 19 (2014) 1536–1550.
- [36] K. Niinimäki, L. Hassi, Emerging design strategies in sustainable production and consumption of textiles and clothing, *J. Clean. Prod.* 19 (16) (2011) 1876–1883.
- [37] J. Ranck, The Wearable Computing Market: a Global Analysis, Gigaom Pro, 2012.

- [38] I.M. Russell, Sustainable wool production and processing, in: R.S. Blackburn (Ed.), *Sustainable Textiles: Life Cycle and Environmental Impact*, Woodhead Publishing 2009, pp. 63–85.
- [39] E.M. Schau, M. Traverso, A. Lehmann, M. Finkbeiner, Life cycle costing in sustainability assessment — a case study of remanufactured alternators, *Sustainability* 3 (11) (2011) 2268–2288.
- [40] K. Schischke, N.F. Nissen, J. Sherry, R. Pamminger, W. Wimmer, Life cycle thinking in small and medium sized enterprises — status quo and strategic needs in the electronics sector, *Electronics Goes Green 2012 +*, ECG 2012 — Joint International Conference and Exhibition, Proceedings 6360527, 2012.
- [41] R. Shishoo, Recent developments in materials for use in protective clothing, *Int. J. Cloth. Sci. Technol.* 14 (3/4) (2002) 201–215.
- [42] Smart Fabrics, <https://www.smithersapex.com/smart-fabrics.aspx> 2011 (accessed on 12-09-2014).
- [43] STS Smart Textiles Salon, Vol. 3 Prototypes on Stage, 06 June 2013, Ghent University, Ghent, 2013.
- [44] M. Suh, K.E. Carroll, N.L. Cassill, Critical review on smart clothing product development, *J. Text. Appar. Technol. Manag.* 6 (4) (2010).
- [45] A. Sule, Life cycle assessment of clothing process, *Res. J. Chem. Sci.* 2 (2) (2012) 87–89.
- [46] X.M. Tao, *Smart Fibres, Fabrics and Clothing: Fundamentals and Applications*, Elsevier, 2001.
- [47] Textales, <https://www.kickstarter.com/projects/434268543/textales2015> (accessed on 26-04-2015).
- [48] E. Tempelman, M. Miodownik, Light touch matters — the product is the interface, *Material Matters*, VII, Material ConneXion, Inc., 2013.
- [49] M. Ten Bhömer, E. Jeon, K. Kuusk, Vibe-ing: Designing a smart textile care tool for the treatment of osteoporosis, in: L.L. Chen, J.P. Djajadiningrat, L.M.G. Feijs (Eds.), *Proceedings of the 8th International Conference on Design and Semantics of Form and Movement (DeSForM)*, Wuxi, China; 22–25 September 2013 2013, pp. 192–195 (Available at: <http://purl.tue.nl/1008278342617491.pdf>).
- [50] M. Toeters, M. ten Bhömer, E. Bottenberg, O. Tomico, G. Brinks, Research through design: a way to drive innovative solutions in the field of smart textiles, *Adv. Sci. Technol.* 80 (2013) 112–117.
- [51] N. Tromp, P. Hekkert, P.P. Verbeek, Design for socially responsible behavior: a classification of influence based on intended user experience, *Des. Issues* 27 (3) (2011) 3–19.
- [52] N.M. Van der Velden, M.K. Patel, J.G. Vogtländer, LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane, *Int. J. Life Cycle Assess.* 19 (2) (2014) 331–356.
- [53] Vogtländer, LCA: A Practical Guide for Students, Designers and Business Managers, VSSD, Delft, The Netherlands, 2010.
- [54] J.G. Vogtländer, H.C. Brezet, C.F. Hendriks, The virtual ecocosts '99: a single LCA-based indicator for sustainability and the ecocosts/value ratio (EVR) model for economic allocation, *Int. J. Life Cycle Assess.* 6 (3) (2001) 157–166.
- [55] J.G. Vogtländer, A. Mestre, R. Van der Helm, A. Scheepens, R. Wever, *Eco-efficient Value Creation, Sustainable Design and Business Strategies*, VSSD, Delft, The Netherlands, 2013.
- [56] T. Walser, E. Demou, D.J. Lang, S. Hellweg, Prospective environmental life cycle assessment of nanosilver T-shirts, *Environ. Sci. Technol.* 45 (10) (2011) 4570–4578.

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Design for Sustainability program

This dissertation describes the PhD research on the envisioned role designers could take responsibility for in the transition towards a more sustainable fashion industry.

The current worldwide textile and apparel system is unsustainable – from both an environmental as well as a social point of view. The clothing industry is associated with (un-)sustainability problems ranging from materials depletion and toxic emissions to social exploitation.

This thesis argues that knowledge about life cycle thinking and life cycle assessment (LCA, as a method to calculate 'eco- and socio-burden') could accelerate the transformation towards a more sustainable fashion production system. Therefore, designers are encouraged to include findings that result from the application of the LCA method, in the fashion design process, with the aim to gain insights into the sustainability hotspots over the clothing products lifecycle. This knowledge can help designers to apply ecodesign and create 'Life Cycle Clothing', and is intended to enhance the self-empowerment based learning and probing process of the designers, the makers and the wearers of fashion. It is envisaged, within the wider context of the national and international governance of the fashion branch sustainable development future, that (i) the analytical methods and ecodesign approaches from this study, together with (ii) the self-empowerment process, will be essential elements (even necessary conditions) for a successful transition.

The conclusions of the research suggest practical guidelines for designers who are willing to adopt a different role than many of their predecessors, and – possibly with help from the trans-LCA-tor – become a frontrunner of sustainable fashion by adding quantitative sustainability assessment to their ‘portfolio of skills’.



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