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LCA on fast and slow garment prototypes

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preface

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A Mistra Future Fashion Report
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summary

This report summarises the environmental assessment work done in the Mistra Future Fashion program focussed on the potential to improve the environmental performance of garments and adapt them to a circular economy. The approaches examined in this report include reducing the environmental impacts from fast-fashion trends by making garments from paper-based materials, or by extending garment life cycles.

This assessment considers two paper-based garments. One is made primarily from paper pulp but enhanced with a polylactic acid polymer. This garment is worn between two to five times before being recycled as newspaper. The other fast garment is made of paper pulp, polylactic acid and nanocellulose. It has a similar life cycle but is composted after use life. These garments are compared with a standard t-shirt. The report also considers a slow-paced scenario in which a polyester garment passes between several owners and is regularly changed to maintain its appeal. It is updated with a transfer sublimation overprint three times, making the garment darker each time. Later it is joined with an outer shell of new material using laser technology to make a cropped, box-cut jacket.

The assessment was performed using environmental life cycle assessment. More particularly, the assessment was based on attributional process analysis with cut-off allocation procedures and comparison with a traditional reference garment life cycle. Key environmental effect categories considered here include climate change (greenhouse gas emissions), freshwater eutrophication, freshwater ecotoxicity and human toxicity (cancer and non-cancer).

The results indicate that the environmental outcomes of the paper-based garments can be competitive with the reference garment, particularly when the user is assumed to throw away a fully functional reference garment after five uses. This assumption may be true for some users, but the number of uses is considerably lower than the typical or the potential lifespan of the reference garment. The main factor assisting the paper-based garments is the reduction in the impacts per mass associated with material manufacturing (fibres, spinning, knitting), and also their lighter masses. Avoided impacts in the use phase play a secondary role on account of their location in Sweden with its low-carbon energy mix. The long-life garments are also competitive compared with their reference garments. This is primarily a consequence of how extending garment life avoids the production of new garments. The environmental impacts associated with transfer sublimation dye reprinting and laser processing do not significantly impact the overall environmental performance of the extended long-life garments, though confidentiality of data prevents a full assessment of these.

The garments in this report are pilot products and explorative scenarios rather than attempts to model existing business or behavioural patterns. The reader should therefore take care to keep the results in context when interpreting them. Nevertheless, the results suggest the value of pursuing the potential associated with these garment life cycles. We should also bear in mind that while the reference garments in this assessment are based on typical usage patterns, other more sustainable patterns are feasible.

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CO2 = carbon dioxide
CTUe = comparative toxicity units for ecosystems
CTUh = comparative toxicity units for humans
LCA = life cycle assessment
LCI = life cycle inventory
LCIA = life cycle impact assessment
ILCD = International Reference Life Cycle Data System
IPCC = Intergovernmental Panel on Climate Change
ISO = International Organization for Standardization
NMVOC = non-methane volatile organic compound
P = phosphorus
PEF = product environmental footprint
PES = polyester
rPES = recycled PES
vPES = virgin PES
PET = polyethylene terephthalate
SO2 = sulphur dioxide
VOC = volatile organic compounds
WWTP = waste water treatment plant

1. introduction

1.1 garment design and life cycle assessment

This report forms part of the Design Theme's work in the Mistra Future Fashion (MFF) program where design researchers and environmental researchers have made a joint effort in overcoming the disciplinary barriers for collaboration in order to bring life cycle assessment (LCA) insights into the design process at the outset. At the beginning of the project a model for "quantified design" was generated (Goldsworthy et al 2016); relevant for designers, design researchers as well as LCA researchers.

The ultimate goal of the project is to find a model where both design and LCA research processes are merged and responsive to one another, building a new framework whereby the impact on the environment acts as an integrated part of the design brief and informs each stage in the design concept development. The immediate goal of this LCA study is to inform designers and the public about the extent to which some prototyped short and long life garments developed in the MFF program provide environmental benefits over reference garment life cycles. (This goal is discussed further in Section 3 of this report in terms of the ISO14040 LCA standard.)

Systems thinking is at the centre of the design model adapted by MFF design researchers in this project. However, unlike the LCA process the 'system' is explored and tested through the realisation of a 'prototype'. In many ways the whole iterative experience of designing can be described as prototypical, although the prototype itself can take on different roles. Design researchers in MFF have been using the 'prototype' as both a 'thinking process' (setting the future scenario) and as a 'proposal for evaluation' (a future product ready to be analysed).

The overarching method for the study involved an integration of the design research and environmental science methods into a combined process which involved iterations of both design concepts and LCA analysis at several points during the development of the designs.

Concepts were originally presented to the environmental scientists as a scoping document which presented the design scenarios in a format which would be helpful for analysis. Several reviews were conducted through discussions over skype which led to further adjustments of both the design concepts and the LCA analysis.

In this report we see the first full LCA review of the concepts as they were originally presented. It represents an interim point in the project from which point the designs have responded to some of the insights gained and been further developed. The conversations and insights which have surfaced during the process will be reflected on in a future review. It is hoped that future collaborations of this nature can be informed by the results of this highly experimental work.

1.2 assessment of alternatives to contemporary fast fashion

Fast fashion is a phenomenon which is blamed for increasing the impact of the clothing sector. Previous LCA work in the Mistra Future Fashion program demonstrated the value of extending the lifespan of garments in order to reduce the need to perform environmentally significant fibre and fabric production steps, among other elements of the garment life cycle (e.g. Roos et al, 2015; Zamani et al, 2017). There is therefore a benefit in imagining how a garment can be constructed so as to achieve greater durability and a longer lifespan. In this endeavour we have to contend with the observation that garments are typically not used to the end of their potential lifespans as defined by their strictly physical properties, for example their ability to provide thermal insulation. A garment may have a longer life in the hands of its original owner, or the hands of others, if it can be refashioned in some way that renews its value to the user. MFF researchers have been imagining ways to give used garments new interest as a part of this work (Goldsworthy and Earley, 2018).

Alternatively, rather than confronting wasteful consumer habits head-on, other ways to circumvent the impacts of fast fashion would be to develop materials with significantly lower impacts during production, and which avoid the barriers to recycling faced by conventional garments. Significant effort is being put into the development of recycling systems for conventional garments within the Mistra Future Fashion program and elsewhere, but at this time some aspects of technological development and many elements of the relevant infrastructure are not yet adequate to create large-scale closed-loop recycling flows, and they may be under development for many years. This prompts the question of whether it may be possible in the shorter term to create new materials that are more easily returned to existing recycling infrastructure after a short life span. In this context, Mistra Future Fashion researchers have been working on paper-based materials with the intent of making garments that can either be recycled as paper, or composted with urban green-waste (e.g. garden clippings). These tasks have been inputs into this report.

This report describes how the prototyped long-life and short-life garments have been assessed from an environmental perspective. We identify the extent to which they represent an improvement over a reference case, and the key parameters which contribute to differences between garments. The results of this report should not be used for any other purposes than those stated in the report. The report deals with prototypes that do not exist at commercial scale.

" The ultimate goal of the project is to find a model where both design and LCA research processes are merged and responsive to one another, building a new framework whereby the impact on the environment acts as an integrated part of the design brief and informs each stage in the design concept development."

2. method
2.1 life cycle assessment (LCA)

The assessment is based on LCA methodology as outlined in ISO 14040 and 14044 (ISO 2006a, ISO 2006b). LCA is an internationally accepted and widely used method capable of assessing a wide range of environmental impacts over the life cycle of products and services. In short, an LCA accounts for all environmentally relevant flows of energy and materials across the system boundaries, from cradle to grave (or cradle to gate, in more limited studies), and uses characterisation methods to "translate" these flows into environmental pressures expressed in impact categories such as climate change, acidification, eutrophication, toxicity and water depletion. In this way, LCA provides an overview of the environmental performance of the studied product and enables the identification of environmental hotspots in the product life cycle. This information can be useful in decision making, such as in prioritising measures for improved environmental performance.

The LCA procedure consists of four steps, as explained below and illustrated in Figure 2.1.

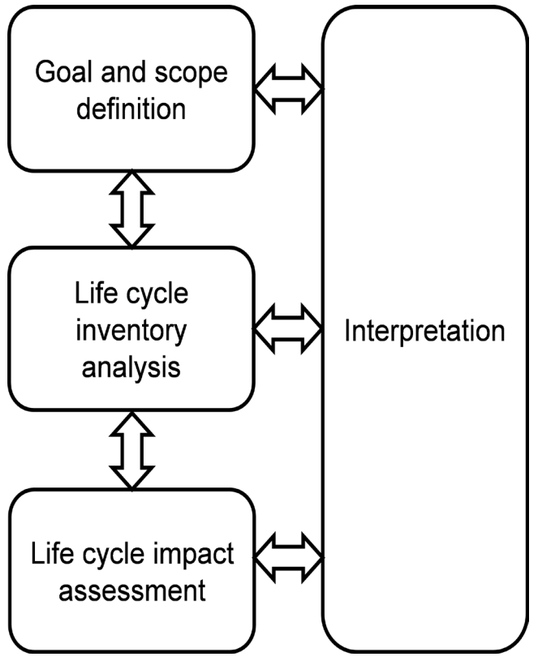


Figure 2.1 Schematic illustration of the four phases of LCA and their interconnectedness.

I. Goal and scope definition: The aim of the assessment, the functional unit and the product life cycle are defined, including boundaries to other product systems and the environment. The functional unit is a quantitative unit reflecting the function of the product, which enables comparisons of different products with identical functions.

II. Life cycle inventory analysis (LCI): All environmentally relevant material and energy flows between processes within the defined product system, and between the system and the environment or other product systems, are quantified and expressed per functional unit. Flows between the defined system and the environment consist of emissions and the use of natural resources.
III. Life cycle impact assessment (LCIA): By means of characterisation methods, the LCI data is translated into potential environmental interventions, classified into impact categories. The LCIA can also include normalisation and weighting, in which results for several impact categories are aggregated on a single yardstick – these steps are not included in the present study.
IV. Interpretation: The result of the LCIA is interpreted, taking into account the goal and scope definition (e.g. the system boundaries) and the LCI (e.g. data gaps and data uncertainties), and recommendations are made to the intended audience.

As illustrated in Figure 2.1, carrying out an LCA is an iterative process, since intermediate results and insights may call for revision of earlier steps.

2.2 modelling approaches

The present study is a process-based LCA, which is "bottom-up" modelling in which the environmental impact of the life cycle is mapped based on its constituting parts – the unit processes – which are modelled separately and in detail. This is in contrast to an input/output (I/O) LCA, in which the life cycle is modelled by assigning a certain share of the flows or impacts of an industrial sector (e.g. Alvarez-Gaitan et al, 2013).

Furthermore, the present study is an attributional LCA. This means that we are attempting to map the product system as it is (or in the case of the present report: as we anticipate it to be), to learn more about the system and its associated environmental hotspots. This is in contrast to a consequential LCA, in which one attempts to map the consequences of a specific change or decision. The choice of an attributional rather than a consequential modelling approach has implications for the definition of system boundaries and the choice of allocation methods. Among others, consequential modelling is more inclined to account for secondary or tertiary affects arising due to market mechanisms.

Also, the study is a prospective LCA, i.e. a study of an emerging, yet non-existing product system (Arvidsson et al. 2017). Such studies are associated with some specific uncertainties, particularly because (i) some processes of the studied system do not yet exist and, in our case, had to be modelled based on pilot or bench scale data combined with some rough estimates on what is possible to achieve in terms of efficiencies; and (ii) background systems (electricity and heat production, production of input chemicals, etc.) change over time, and may therefore be rather different at a time when a commercial scale system has been realised.

2.3 allocation procedures

An important choice when conducting an LCA is how to allocate the environmental burden of multi-functional processes between the functions. How to solve such allocation problems is particularly an important choice in studies of products made from recycled feedstock. The key question is whether the incoming recycled (pre- or post-consumer) textile material should be considered to be responsible for any environmental burden of its previous life cycle (primarily, the initial raw material extraction) or whether it should be considered to be free of environmental burden from its previous processes.

The first option reflects a view that the recycled material is a co-product of the previous product system, and that, for example, the economic profit of the previous product system, and therefore the demand for it, is influenced by the subsequent recycling of the material. The second option reflects a view that the recycled material is a waste that has no (or negligible) economic influence on the previous production system and should thus be considered to be free of environmental burden. The second option can be described as "cut-off allocation". If the first option is chosen, the recycled material should be allocated a share of the burden of the initial raw material extraction (then a new allocation problem arises: how this share should be decided).

The second option for allocating the recycled material has been identified as the most common allocation procedure in LCAs of textile recycling in a recently published literature review (Sandin and Peters 2018), and is therefore chosen as the baseline option in the present study. Sandin and Peters (2018) also show it is common practice to apply system expansion and assign credit to the studied product because the presumably replaced production of some product from virgin materials. This approach is therefore also adopted in this study.

2.4 impact categories

In LCA, there is a wide range of impact categories to potentially include. For each impact category, there are several characterisation methods to choose from. In the present study, the choice of impact categories and characterisation methods is based on the choices made in a previous Mistra Future Fashion report (Roos et al. 2015), a selection that reflects important environmental issues facing the textile industry.

Some modifications have, however, been made. Energy use was initially included, to be able to identify the energy hotspots in the system, which in contrast to other energy-related indicators is independent of the assumed dataset for background processes (e.g. for electricity and heat production). However, this and acidification potential are not presented graphically as the outcomes follow patterns presented by the climate change indicator. Water use was not assessed in this work for several reasons. One is that the long-life garments are all made of synthetic materials, which do not demand significant water use. On the other hand, in modern LCAs that take regional water availability into account, forest products without irrigation are demonstrably superior to artificially irrigated cotton (Sandin et al, 2013) and water use for cotton cultivation dominates the life cycle of a t-shirt used in Sweden (Roos et al, 2015) so it is a foregone conclusion that the comparison between the short-life garments will favour the paper garments over the reference garment.

Furthermore, data was obtained for this LCA from both Ecoinvent and Gabi Professional databases, which do not handle the latest water impact assessment methods consistently. Table 2.1 lists the selected impact categories and characterisation methods. The impact categories are further described in Appendix 1.

Table 2.1: Selected impact categories and characterisation methods

Impact category	Characterisation method	Unit	Reference for characterisation method
Climate change	Global warming potential with a 100 year perspective (GWP100), excluding biogenic CO2 emissions	kg CO2 equivalent	IPCC (2013) as implemented in Gabi IPCC (2013) as implemented in GaBi (ILCD PEF recommendation, v1.09)
Acidification	Accumulated exceedence	Mole H+ equivalents	Seppälä et al. (2006) and Posch et al. (2008) as implemented in Gabi
Freshwater eutrophication	Freshwater eutrophication potential (EUTREND model)	kg P equivalents	Struijs et al. (2009) as implemented in Gabi
Freshwater ecotoxicity	Ecotoxicity potential (USEtox model, recommended + interim)	Comparative toxic units for ecosystems (CTUe)	Rosenbaum et al. (2008) as implemented in Gabi
Human toxicity, carcinogenic	Human toxicity potential (USEtox model, recommended + interim)	Comparative toxic units for human (CTUh)	Rosenbaum et al. (2008) as implemented in Gabi
Human toxicity, non-carcinogenic	Human toxicity potential (USEtox model, recommended + interim)	Comparative toxic units for human (CTUh)	Rosenbaum et al. (2008) as implemented in Gabi
Energy use	Primary energy from renewable and non-renewable resources (net. cal. value)	MJ	Primary energy from renewable and non-renewable resources as implemented in GaBi

2.5 software and LCI databases

The Gabi Professional software, developed by ThinkStep, was used for modelling the product system and calculating the LCIA results. The Gabi Professional (version 8.5, service pack 35) and Ecoinvent 3.3 databases provided LCI data for the background processes.

2.6 limitations

Like many LCAs, the accuracy of this report is limited by life cycle data availability and ongoing methodological debates.

A fundamental issue for life cycle inventory data collection for this study is that it is an attempt to look forward to garments that do not yet exist in the commercial market-place. Therefore, it is essentially an examination of scenarios developed to understand the potential of particular future options. On the other hand, in some cases (e.g. printing) data requested by the team was not supplied by commercial operators and therefore some quantitative assumptions had to be made. (This is discussed in Section 4.3.). Building rational assumptions about systems based on today's technologies is a worthwhile approach to grounding an LCA in reality. On the other hand, for example in the case of the long-life jacket which is not going to be made for at least 15 years in our scenario, also it represents a limitation to the study.

Studies like these are dependent on the use of life cycle inventory data collected by other analysts and compiled in the databases named in Section 2.5. This may introduce errors. For example, the paper pulp data available in the Ecoinvent 3.3 database has been under scrutiny in work on Product Environmental Footprint Category Rules led by the European Commission, and the amount of primary energy from renewable resources has been discovered to be considerably higher than expected when compared to unpublished confidential data sources. The proposed explanation to this is double counting of forest resources used for feed-stock and energy. In the calculations, this may lead to an overestimation in primary energy from renewable and non-renewable resources for the paper-based short-life garments. The research team also believes that phosphorus emissions suggested in Ecoinvent associated with coal production may be an overestimate. There may be other issues of which we are unaware.

A key methodological uncertainty in LCA concerns the choice of attributional or conse-quential approaches. For an introduction to these ideas, see Baumann and Tillman, 2004. Many LCAs include features of both approaches. In this LCA we have attempted to adopt an attributional approach as far as possible, however the norm of conside-ring that by-products generate benefits through the creation of avoided products is arguably a consequentialist feature of this work.

There are other uncertainties associated with the use of linear impact characterisation factors in LCA and the underlying models used to calculate them. This report reflects contemporary LCA practice, but the models are subject to improvement in the future.

3 goal and scope definition
3.1 goal

The aim of this LCA is primarily to inform public debate and clothing designers regarding the potential to reduce environmental damage by interventions in garment designs. More specifically – the goal is to find out to what extent the prototyped short and long life garments developed in the MFF program provide benefits over reference garment life cycles. We aim to make this comparison, identify key process hotspots and parameters of interest for life cycle optimisation of garment designs and policies towards a circular economy.

3.2 audience

The report is intended for designers and strategic planners within the fashion and public sectors. In the first place these are persons among the MFF consortium's researchers and corporate partners. This research is a curiosity-driven activity which is not directly coupled to a particular decision-maker nor the making of claims for the marketing of a particular commercial product. On the other hand, it is also intended to inform public debate around fast fashion, and has strategic consequences for the design of sustainable fashion.

3.3 functional unit

In LCA, a functional unit is an attempt to provide a quantitative definition of the basis for comparing alternative systems. In this study. the functional unit is defined as a single use of a garment. Although the garment may be used several times, by scaling the impacts of the whole garment life cycle to this functional unit, we are better able to compare a garment that provides its function for a short time with another garment with a longer life. This functional unit also facilitates comparison with garments previously studied in Phase 1 of the program in which the same functional unit was applied. When considering the long-life garments, the functional unit is defined in the same way, with the caveat that two different kinds of garments are in use (a blouse and a jacket).

Some additional functional units are used in specific places in the report, including the use of the short-life garments over a year, and the use of the long-life garments over 30 years. In the case of both of these presentations of the results, the intent is to show how the longevity of the garments influences the environmental outcomes.

3.4 system description

The scenarios described in this section of the report are the result of an iterative discussion between British researchers with expertise in textile design (Dr Kate Goldsworthy, Professor Kay Politowicz and Professor Rebecca Earley at University of the Arts, London), paper expert Hjalmar Granberg (RISE, Stockholm) and other Swedes with expertise in sustainability assessment (Professor Greg Peters at Chalmers University of Technology, Dr Gustav Sandin Albertsson and Mr Björn Spak at RISE, Dr Sandra Roos at Swerea IVF).

Throughout this work, these scenarios are considered to be potential future scenarios. Whether or not they are ultimately practical is a question since we are working in a speculative design process. We have attempted to avoid creating scenarios that can obviously only exist in the imagination. Nevertheless, we will assume the existence of certain industrial processes for the new materials in the short-life garment, and certain behavioural habits necessary for the long-life garment. These need not exist today, but may exist in the future. Our task is not to report on what has been demonstrated to work, but to find out whether some ideas about the future are attractive from an environmental perspective.

3.4.1 overview of life cycles

Basic data for the garments in this study are shown in Table 3.1. The life cycles of the multi-printed long life blouse and the re-assembled long life jacket are linked and include several transfers of ownership and remanufacturing steps, which are summarised in greater detail in Table 3.2 and described in Section 3.3.3.

Table 3.1: Summary of short and long-life garment life cycles

Garment	Mass (g)	Material type	Key raw materials by mass	Total uses (1)	Washes
paper-based shirt life garments					
Compostable short life garment	58	Nonwoven	57% polylactic acid 40% paper pulp 3% cellulose nanofibrils	5	Nil
Recyclable short life garment	58	Nonwoven	95% unbleached paper pulp 5% polylactic acid	5	Nil
extended long-life garments					
Multi-printed long-life blouse	200	Woven	100% polyester	180	90
Reassembled long life jacket	1500	Woven & nonwoven	200 g polyester from blouse 910 g new polyester 390 g polyurethane	90	3

(1) These initial values were varied in for sensitivity analysis, as discussed in Section 4.6.

Reference garments

Reference short life garment	110	Knitted	100% cotton	22	11
Reference long life blouse	173	Woven	100% polyester	See Table 3.2	Each 2nd use
Reference long life jacket	446	Woven & non-woven	200 g woven polyester 910 nonwoven polyester 390 nowoven polyurethane	See Table 3.2	Each 30th use

3.4.2 short life garments

Consistent with the study goal, regarding the short life garments, the key focus point is whether the use of material that is more easily made and recycled than ordinary garment material, makes a super-fast life cycle environmentally preferable to a reference garment. The garment needs to be compostable or recyclable, so if elements of wet processing (e.g. dyeing) would render it non-compostable (perhaps due to toxicity) then this would take the garment out of consideration for this scenario. So we have attempted to avoid toxic dyes in the garment designs.

Figure 3.1 and Figure 3.2 illustrate the key elements of the life cycles to be considered for the two paper-based short life garments. There is a difference of composition between them, with the compostable garment containing 57% polylactic acid (PLA), 40% cellulose pulp and 3% nanocellulose, while the recyclable garment is 95% cellulose pulp and 5% PLA. In both cases the PLA is a corn-based biopolymer. The production processes are assumed to take place in China for consistency with the reference garment (to eliminate the influence of geography as an additional variable in the comparison), while the use and disposal processes for all garments occur in Sweden. (The dotted line from electricity production is dotted only to make it clear that e.g. wax is not used after material production.)

Naturally, not every detail is shown in these simplified figures, in terms of energy nor material flows. Note that in Figure 3.1, it is common to consider organic soil additives produced as a by-product of waste management in terms of their nitrogen and phosphorus content and the avoidance of mineral fertiliser production, however, the main product in the figure consists mostly of carbon and oxygen, so the appropriate avoided product associated with the production of compost is assumed to be a carbon source used in the production of horticultural compost (peat).

Figure 3.1: Basic flowchart - Short-life compostable garment

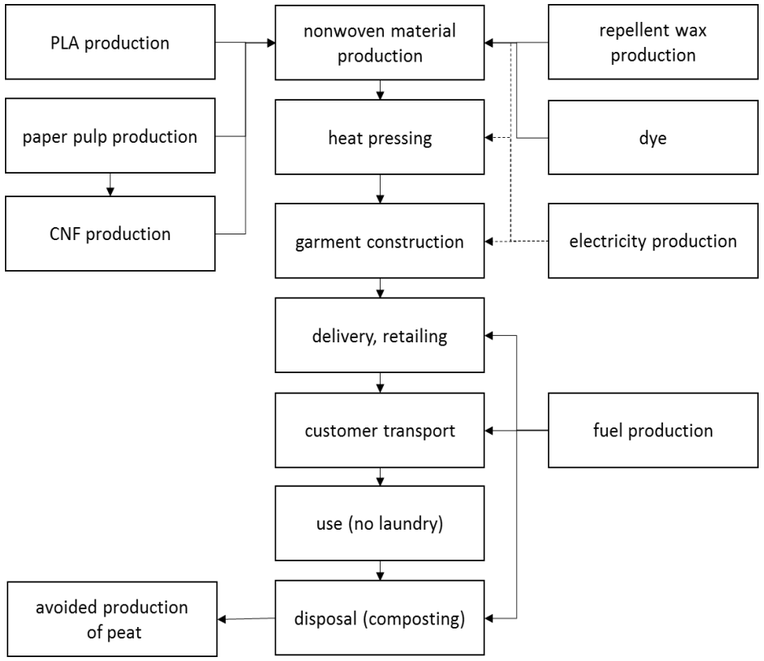
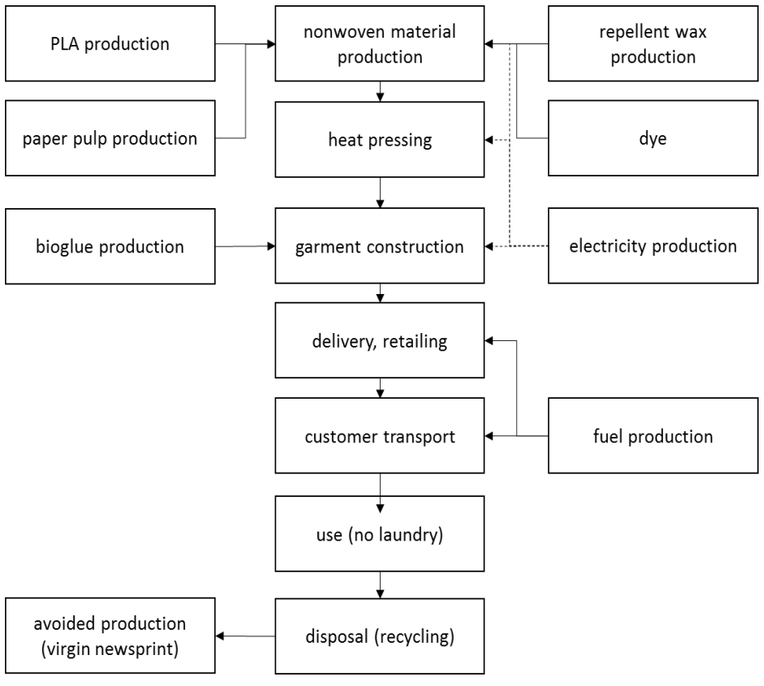
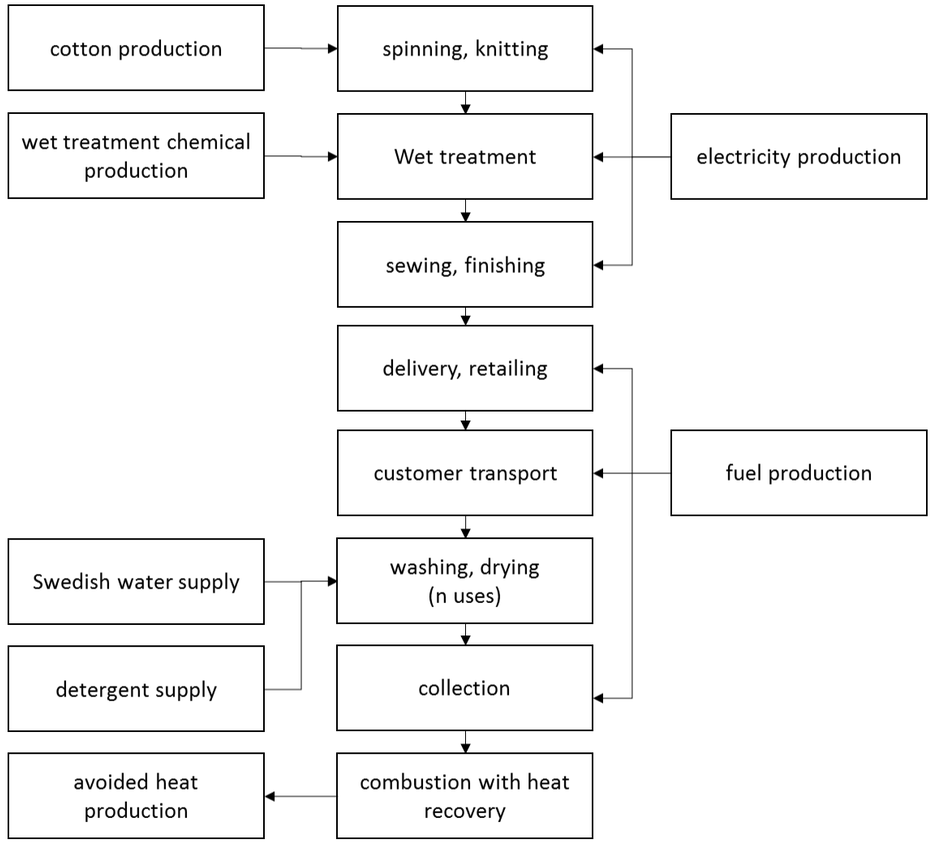


Figure 3.2: Basic flowchart – Short-life recyclable paper garment



We have based the reference short-life garment on the life cycle assessment work in the first phase of the Mistra Future Fashion program (Roos et al, 2015). The short-life reference garment is shown in Figure 3.3. The garment is assumed to have production processes located in China but its use phase in Sweden. The number of uses is initially assumed to be five – this assumption was examined in a sensitivity analysis and is discussed 5.1. Standard waste management in Sweden is combustion with municipal solid waste, with energy recovery for district heating.

Figure 3.3: Reference garment for short-life comparison



3.4.3 long life garments

Although we regard the long life scenario as one scenario for the purposes of this report, it is in fact several garment life cycles rolled together (a plain blouse, three printed blouses and a blouson). Furthermore, our principal interest is in the transformational processes (sublimation overprinting and laser processing for transformation of one garment to another) as means for renewing the garments' value to the owners. Another aspect of the long life scenario is the business model in which garments are repeatedly returned to one or several fashion businesses. The sensitivity of the environmental outcomes to key parameters in such models has already been examined from an LCA perspective in Mistra Future Fashion (Zamani et al, 2017), so here we focus on the new garment transformation questions.

The eight subordinate life cycles incorporated in those of the long life garments are summarised in Table 3.2 – a simplified version of the second table in the document "Concepts: fast and slow" (Goldsworthy and Earley, 2018). The principal changes are that the LCA makes more conservative assumptions about the number of times a garment can be worn, and leaves out one additional cycle in the story of the garment for simplicity and ease of comparison with reference garments.

Cycles	Design	Production or rework	Use	Disposal
Cycle 1: Original Purchase	Robust, light/cream coloured blouse.	100% recycled PET	1 - first user 5 years Worn 60 times (once a month)	Shared within family circle
Cycle 2: Passing On #1	-	No change	2 - Daughter of first user 3 years Worn 36 times (once a month).	Overprinting by brand, returned to owner
Cycle 3: Remanufacture #1	Overprint based on trends or user-driven prints	In-store digital dye sublimation overprinting	2- Daughter of first user 2 years Worn 24 times (once a month).	Shared within friendship circle
Cycle 4: Passing on #2	-	No change	3 - Friend of daughter of first user 1 year Worn 12 times (once a month)	Donated back to shop for remanufacture
Cycle 5: Remanufacture #2 Remanufacture #2	Overprint based on trends or user-driven prints	In-store digital dye sublimation overprinting, darker than last time	4 – new user 2 years Worn 24 times (once a month)	Donated back to shop for remanufacture
Cycle 6: Remanufacture #3	Overprint – this time it ends up black	In-store digital dye sublimation overprinting	5 – new user 2 years Worn 24 times (once a month)	Donated back to shop for remanufacture
Cycle 7: Remanufacture #4	Blouse converted to blouson jacket	Sonic welded with another polyester fabric. The detailing may include a melt sequin finish.	6 - New user, limited edition range 10 years Worn 60 times (6 times a year).	At the end of this cycle the garment is either donated to a friend or resold.
Cycle 8: Last ride	-	Cleaning & mending may be needed.	7 new user 5 years Worn 30 times (6 times a year).	Combustion with heat recovery.

The life cycles are based on the idea that a simple, light coloured but robustly constructed polyester garment is firstly handed down a generation within a family before being remanufactured in-store via addition of a printed design. It is later passed to a friend of the second owner. There are two more reprinting and retailing steps and each time the garment passes to a new owner. Finally, the garment is remanufactured by laser processing to join it with additional polyester and polyurethane material (e.g. a synthetic microfiber fabric such as Ultrasuede), to create a blouson jacket. Like the first two versions of this garment, the jacket also has two users.

Figure 3.4 to Figure 3.8 show the various life cycles within this scenario in more detail. Note that it is assumed that when the garment is transferred between owners in the first and second, and the third and fourth cycles, these happen without additional transportation effort, since these people are either in a family or a close friendship, so they are already in regular contact and the garment is exchanged when users happen to meet for other reasons.

Figure 3.4: Multi-printed long life blouse - life cycles 1&2

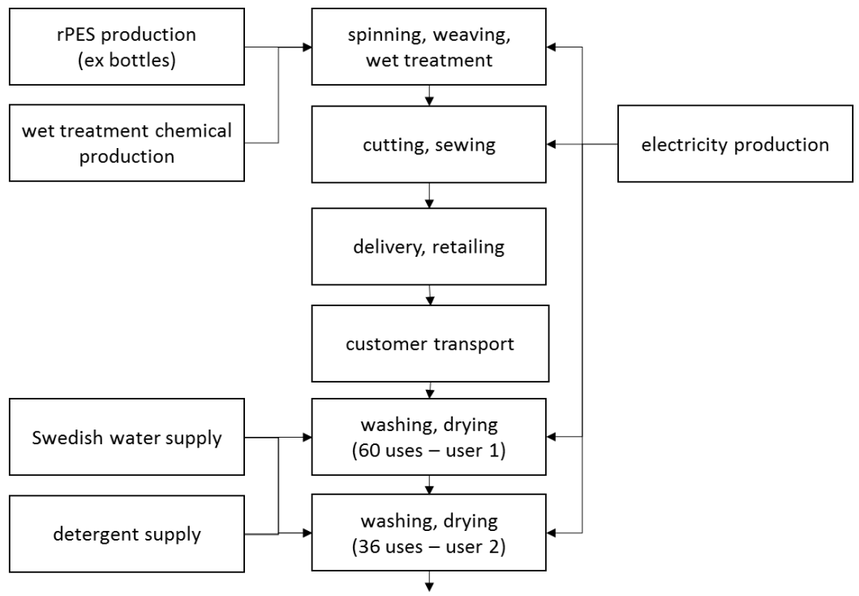


Figure 3.5: Multi-printed long life blouse - life cycles 3&4

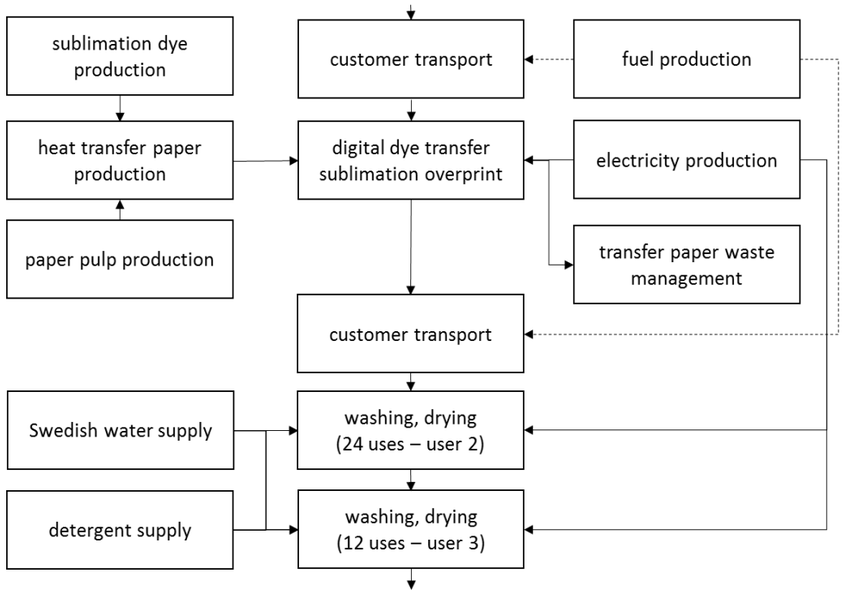


Figure 3.6: Multi-printed long life blouse - life cycles 5,6

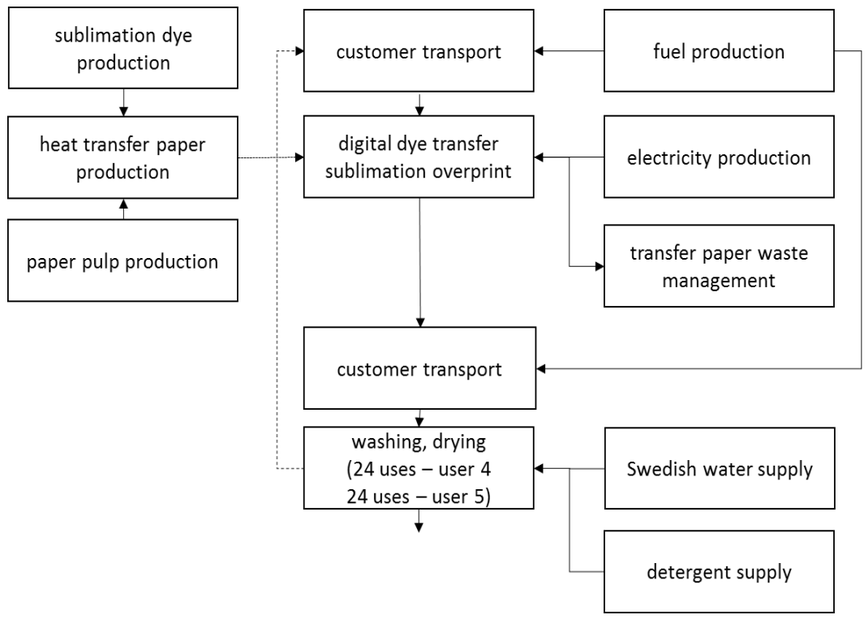


Figure 3.7: Reassembled long life jacket - life cycle 7

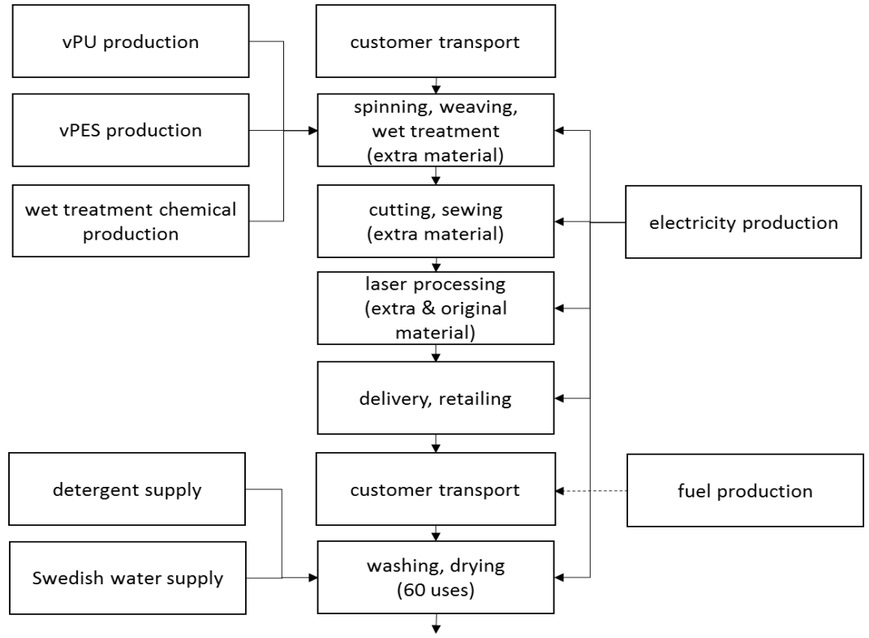
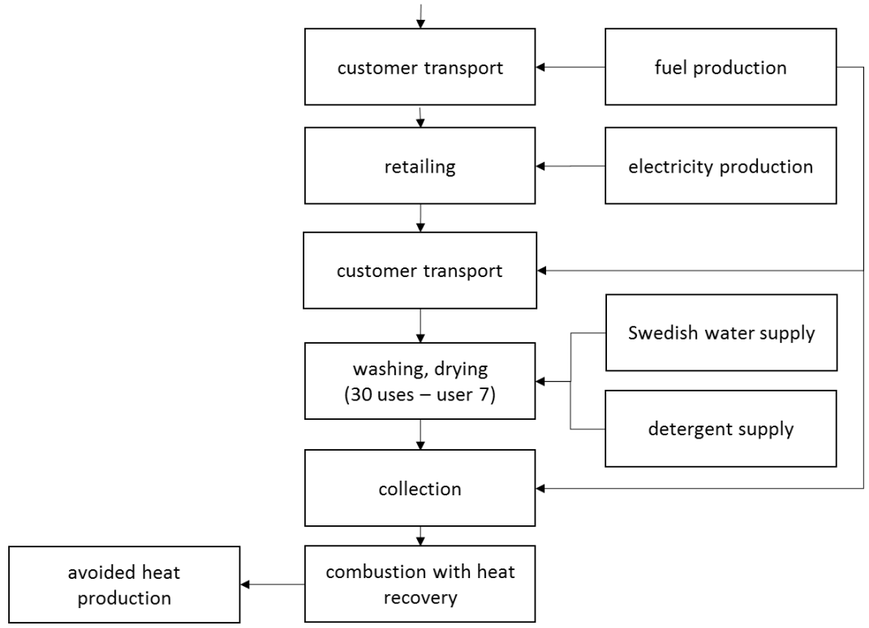


Figure 3.8: Reassembled long life jacket - life cycle 8



The life cycles that are to be compared with these are shown in Figure 3.9 and Figure 3.10 and summarised in Table 3.3. So in each of the reference scenarios for cycles 1-6, a new polyester garment is created, used and destroyed (cf Table 3.2 with Table 3.3). Likewise, in both reference scenarios for cycles 7 and 8, a new blouson jacket is made, used and destroyed. These are basically shorter-lived versions of the long-life garments that are disposed of after use. The number of uses is chosen to be consistent with the number of uses the garments in the long-life scenario get in each life cycle. The production of the blouson is based on the same technology as the blouson in the long-life scenario, with the difference that virgin polyester is used for both key elements of the garment. Other differences have to do with the use of virgin polyester and traditional dyeing approaches for cycles 3 and 4.

Table 3.3: Summary of reference long life garment life cycles

Reference garment cycles	Design	Use	Disposal
1-6	vPES blouse	12-60 uses (cf Table 3.2)	Combustion with heat recovery
7-8	vPES/PU blouson jacket	30-60 uses (cf Table 3.2)	Combustion with heat recovery

Examining these reference life cycles by themselves without considering the long garment scenario one may ask whether the number of uses per garment is appropriate. As a future scenario, we cannot be sure how often a garment will be used, but the range of uses (12-60 within reference life cycles 1-8) is expected to allow the importance of this variable to be additionally illustrated in this analysis.

Figure 3.9: Baseline for long life garment - cycles 1-6

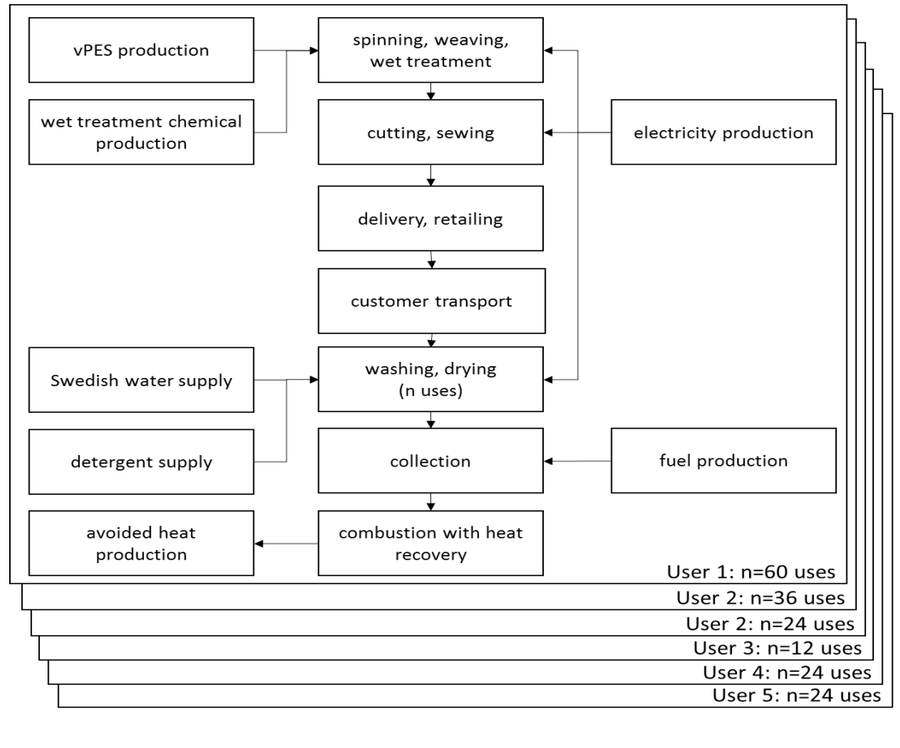
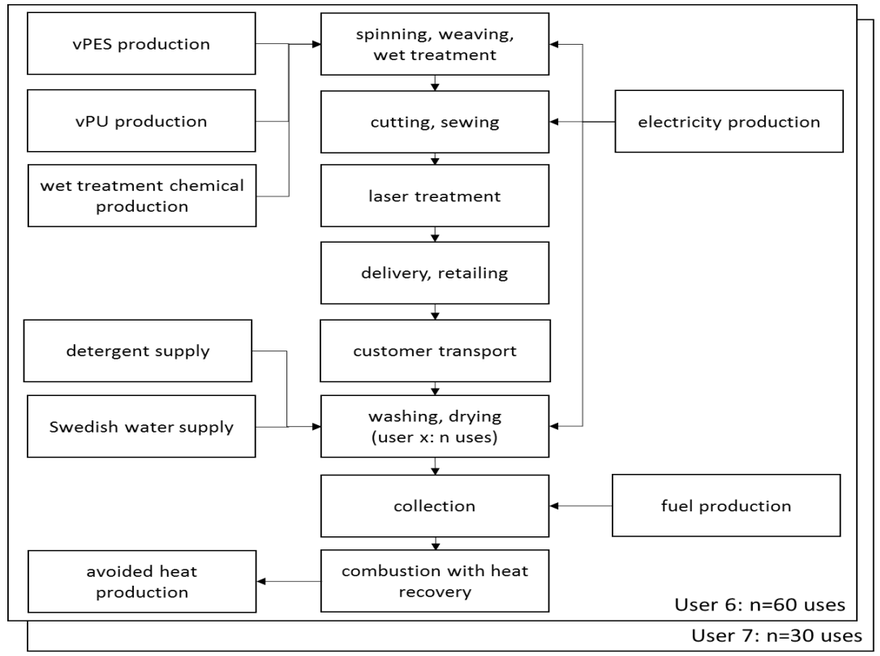


Figure 3.10: Baseline for long life garment - cycles 7&8



3.4.4 comparison with statistical data

Swedish national statistical data was reviewed as a reality check for the scenarios used in this LCA. These data are most relevant for the evaluation of the reference garments, since the other garments in this study are not currently on the market. Nevertheless, we wanted to hold the number of uses per garment life cycle constant between the reference garments and the alternative life cycles, to reduce the number of variables affecting the outcomes. Therefore, the statistical data has a bearing on the garments.

Data was previously obtained for the short-life reference garment as described in Roos et al (2015). This indicated that this garment would on average be used 22 times.

Regarding the long-life garments, data was obtained from Statistics Sweden (SCB, 2018) describing imports and exports of blouses and jackets. Detailed data associated with an 8-digit product identifying codes was analysed. While the 8-digit data has the advantage of including information on the mass and number of garments, and can therefore be used to estimate the typical mass of garments, this detailed data is not corrected for missing reports by traders, which makes it less appropriate for the assessment of total consumption. The detailed data indicated an average mass of 173 g per blouse and 446 g per jacket in 2017. In accordance with the Mistra Future Fashion design team's prototypes for long-life garments, the corresponding garments in this study were initially assumed to be heavier, weighing 200 and 1500 g respectively, prior to a sensitivity analysis using the SCB masses.

Data for trade in blouses defined by 4-digit codes (6106 and 6206) was obtained and the difference between imports and exports was taken as the estimate of national consumption. These data indicate that Swedish women consumed 3871 tonnes of blouses in 2017. If these garments have an average mass of 173 g and are spread evenly among 5 million women, this means each woman buys 4.5 blouses per year. Since the fashionable blouson jacket considered in this LCA is quite different from the fashion and functional garments aggregated by the relevant 4-digit codes (6104, 6204), we looked instead at 6-digit codes (for 610431, 610432, 610433, 610439, 620431, 620432, 620433, 620439) which indicated that Swedish women consumed 1465 tonnes of fashion jackets in 2017. Given the same population and a garment mass of 446g, this indicates each woman buys one every 18 months.

If we assume that the long life blouse is used 180 times over 15 years, this implies the first user uses it 60 times over 5 years. Since she buys 4.5 blouses per year, her implicit wardrobe size is 23 garments. If the blouson jacket is used 90 times over 15 years, this means the first user uses it 60 times over 10 years. Assuming this use rate and a purchase rate of one fashion jacket per 18 months, this means she has an active wardrobe of 7 such garments. While we have no independent data with which to compare these wardrobe sizes, they seem feasible. If the assumed number of uses is increased above these levels, we are faced with the likelihood that the long life garment might not survive the entire length of the scenario. If we decrease the number of uses we have the potential alternative problem of unrealistically large wardrobes.

4 inventory analysis

Life cycle inventory data describes the physical and energetic flows between processes within the life cycle of a system. In the case of this work, the systems under study are described in section 3.3. By processes we mean the engineered and user activities indicated by the figures in that section. Data representing many of these (garment construction, delivery, retailing, customer transport and garment use) are described in detail in Roos et al (2015) and are not repeated here. Data for other key processes is described in this section of the report.

4.1 cellulose nanofibrils

The inputs to the production of one tonne of cellulose nanofibrils for the short-life compostable garment were modelled as 1 tonne of elemental-chlorine free bleached pulp, 1336 kWh of electrical energy (Karpenja, 2018). A further 170 g of enzymes used in the process were considered insignificant. Some analysts (e.g. Gilpin and Andrae, 2016) have demonstrated that the intense production process for enzymes can lead to a significant contribution to the cradle to gate life cycle impacts of bioproducts, but in this case the mass of enzymatic inputs relative to other inputs is two orders of magnitude smaller than the relative mass in the life cycle inventory of Gilpin and Andrae (2016).

4.2 dyeing

Preliminary assessment suggested that natural indigo dyeing of the paper-based short life garments would be interesting to contrast with chemical indigo dyeing of the reference short-life garment. Buckthorn and cochineal were also considered. Natural indigo production from for example the Indigofera tinctoria plant biomass requires fermentation of biomass, oxidation of fermented broth, settling of oxidized product (indigo), filtration and recovery. Dutta et al. (2017) describes a process with biomass fermentation for 12 h at 40 °C incubation temperature yields the highest biogenic indigo (2.84 mg/g) out of the different experimental conditions. In this LCA we make the assumption that the dye is added to the paper-based garments during paper-making.

Overall, dyeing presented a challenge for this work in terms of identifying reasonable life cycle inventory data. A search for studies containing life cycle inventory data on indigo manufacturing rendered no results, neither in Scopus nor Google. Therefore, it was assumed that the process of extracting the natural dyestuff can be modelled with the cultivation of other plants as a proxy. An average for flax, hemp and jute data presented by Sandin et al (2018) suggested a contribution to climate change of 2.66 kg CO2-e per kg of dye.

Adding the dye to the pulp at the start of the process implies that the traditional dyeing and subsequent drying steps are completely removed from the life cycle of the paper-based products. This is in contrast to woven textiles and knitwear where there will still always be a finishing step to wash away needle oils or sizing agents and dry the product. Generally, the temperature of the paper process should not be a problem for the dyes. The water holds a temperature around 60-70°C which is below the temperature at which the natural dye process occurs. While this is promising, the technical feasibility of the process is not certain because indigo is not water soluble unless reduced and has poor affinity to cellulose. For textile indigo dyeing a sequence of reduction/oxidation steps are carried out.

For the purpose of this study, it is assumed that the selected dyestuff will act as a direct dyestuff in the paper pulp and have no problems with bonding to the material. The use of a pulp dye process implies that no larger changes are needed for adding dye to the pulp before paper making. The yield will be the same (contamination of colour to new pulp is negligible) and the water recycling rate is also the same. It is assumed that 2% indigo is added to the process together with a fixing agent (in this case aluminium sulphate though cationic polymers can also be used) added at the same rate.
It is assumed that 95% of the dye stays on fabric and that the waste water treatment plant has 90% efficiency, which gives small emissions of indigo (0.1 g per kg paper produced) and aluminium sulphate (2 g per kg paper produced). Neither of these emissions have any impact on the total ecotoxicity.

4.3 sublimation printing

The sublimation printing process was modelled using mainstream components. Epson is a popular brand for dye sublimation transfer printers. The SureColor F6200 printer was chosen as a mid-sized (44 inch) printer suitable for most garments and at about USD 8500 about a half of the price of the next largest (64 inch) printer in their range. Another reason to choose it for this scenario modelling is the relatively non-toxic ink the Epsom printers apply. It uses 1 L ink packs (cyan, magenta, yellow, black) and is claimed to print 325 square feet per hour (8.125x10-3 m2.s-1) at its midrange “production” pixilation of 720x720 dpi (selecting “high quality” or “speed” operation” doubles or halves the pixel density, respectively).

If a garment has a printable area of 0.5 m2 this would imply the printer is in operation for about one minute per garment. Operating power consumption is 65 W, 3 W on standby. As a starting point we assume 20% utilisation of the printer – in other words, for each minute of operation, four minutes of standby power are drawn. Thus the power consumption of the printer is 1.3 Wh/garment. The printer uses water-based UltraChrome DS ink which Epson says is Oeko-tex certified when applied to polyester fabric. Information from the MSDSs for the dyes is shown in Table 4.1. An average dye composition was used in the LCA based on an equal mix of the four colours and the stated ranges of their ingredients.

Typical drop size specifications for printers like these are in the range 2-240 pL and the actual size depends on operational choices and the printer head. Epson claims a minimum of 5.3 pL for this particular printer but states no maximum size. Assuming the minimum corresponds to the “high quality” mode, the pixilation implies an ink application rate of 8.5 mL.m-2. If this application rate is maintained in “production” mode, the drop size is 10.6 pL. (During the preparation of this report, Epson was contacted with a view to improving the application rate estimate, but the company refused to contribute any estimate. We therefore consider this to be a low estimate of potential ink use.)

Table 4.1: Principal components of sublimation dyes

Substance	CAS number	Black	Yellow	Cyan	Magenta
Water	7732-18-5	50-65%	60-65%	60-65%	60-65%
Glycerols	56-81-5	15-20%	20-25%	20-25%	10-15%
Organics	-	0.25-0.5% Triethanol amine (CAS: 102-71-6)	10-15% of which 3-7% propylene glycol (CAS: 57-55-6)	10-15% of which 3-7% propylene glycol(CAS: 57-55-6)	10-15% of which 3-7% propylene glycol(CAS: 57-55-6)
Dyes	-	1-5% CI Disperse Blue 360 (CAS: 70693-64-0)	1-5% proprietary dye	1-5% proprietary dye	5-10% proprietary dye
TEGMME (2)	112-35-6	-	1-5%	1-5%	1-5%

Epsom's DS Transfer Production paper is 75 gsm. We assume a sheet 900x600 mm is used per side of the garment, thus 81 g of paper per garment. The paper and garment are inserted in a typical horizontal heat press, like an Adkins Alpha Industrial Series 7, operating at about 180ºC, taking about 3 minutes per garment. The press draws 9 kW during operation and an average of 68 L/minute of compressed air at 4 bar (Adkins, 2018).

Dye constituents which are regarded as proprietary information have not been quantitatively evaluated due to lack of information. For the Disperse Blue 360, a warning statement is issued by the European Chemicals Agency (ECHA) of risk for allergic skin reaction. This has however not been included in the quantitative life cycle assessment but is discussed further in Section 5.3.

4.4 laser cutting

The conversion from blouse to jacket for the long life garments is based on a standard carbon-dioxide laser which is assumed to operate for one hour for each garment. As a representative laser table machine, the Morn MT-L960 was selected. It has a working space of 900x600 mm and power configurations from 60 to 130 W. This is comparable for our purposes to the Universal Laser Systems 9.150D or Ultra 9 models. These lasers are air cooled and require no "cutting gas" for operation. LCI data was extrapolated from Kellens et al (2014) to generate the electricity and NOx data for the operation of a 75 W laser system shown in the table.

These laser systems also require attachment of an exhaust air filter such as the BOFA AD Universal, for example. To overcome the filter backpressure, the filter fan consumes almost as much energy as the laser, and needs replacement glass and activated carbon filters after use. We assumed a nominal replacement rate of once per thousand garments for the filter materials. Other consumables are considered insignificant, including the replacement of the small quantity of laser gas (carbon dioxide, helium and nitrogen) after 5 years of operation (Igler, 2018). The filter is claimed to eliminate 99.995% of particulate emissions (BOFA, 2018). Nitrogen oxides were assumed to be unaffected.

(2) triethylene glycol monomethyl ether

Table 4.2: Life cycle inventory of laser cutting process

Flow	Value	Unit
Inputs		
Electricity (laser table)	1.8	kWh/hr
Electricity (air filter)	1.1	kWh/hr
Activated carbon	11	g/hr
Glass fibre	2	g/hr
Mild steel filter housing	0.5	g/hr
Emissions		
NOx	5.8	mg/hr

Note that the lasers described in Kellens et al (2014) are an order of magnitude more powerful than the kind that would be used in this textile life cycle model. In accordance with the descriptions of the Morn and Universal Laser Systems lasers they therefore do not require a continuous supply of cooling water, nor laser gas.

4.5 repair

The repair of the reassembled long-life jacket is modelled as a return to a commercial environment in the same manner as the retailing is modelled in other scenarios in this work. The consumer's transport to the repair workshop is modelled as the standard travel arrangement in Roos et al (2015) with 17 km of bus (50%) and car (50%) travel, including the return trip, per kg of purchased garment. The garment is washed and air-dried. A gram of polyester thread is arbitrarily included to represent the repairs – this is a low mass but at 200 dtex would represent fully 50 m of thread.

4.6 sensitivity analysis

The most critical uncertain inventory data in this LCA is considered to be the number of uses of the short life garment. To cope with uncertainty around the actual number of uses for each garment, the analysis in this report is based on a high and low impact estimate:

(a) High impact estimate = 5 uses of the reference short life garment, 2 uses of the paper-based short life garments

(b) Low impact estimate = 22 uses of the reference short life garment, 5 uses of the paper-based short life garments

The assumption of 22 uses of the reference short life garment for the low estimate is consistent with recent statistical information about average Swedish garment use (Roos et al, 2015) while five uses of the paper-based short life garments is the suggestion of the design team.

The high impact estimate is based on more pessimistic assumptions – that a consumer uses a t-shirt for less than 25% of its average lifepan (perhaps a tenth of its potential technical lifespan) representing the faster end of the market – and the paper-based short life garments for 40% of its intended life (which might be the case, for example, due to sweat and odour accumulation in these unwashable garments).

Based on these ratios, this comparison may be biased in favour of the short life garments. However it is feasible to propose alternative reference garments, and in the absence of any user data on the new paper-based materials we may see these estimates as an attempt to bracket the potential use phases for each garment given the inherent uncertainties associated with forecasting.

Given the significance of production processes in the impacts of garment life cycles, another key variable affecting the impacts of all garments is their mass. Initial settings for garment masses were based on the garment descriptions provided to the authors and SCB data. Subsequently we tested the influence of on those results by making the masses of the paper-based and reprinted garments equal to the masses of their reference garments. This is shown in Table 4.3.

Table 4.3: Garment masses for sensitivity analysis

Garment	Initial (g)	Alternative (g)
Compostable short-life garment	58	110
Recyclable short-life garment	58	110
Reference short life garment	110	110
Multi-printed long-life blouse	200	173
Reference long-life blouse	173	173
Reassembled long-life jacket	1500	446
Reference long life jacket	446	446

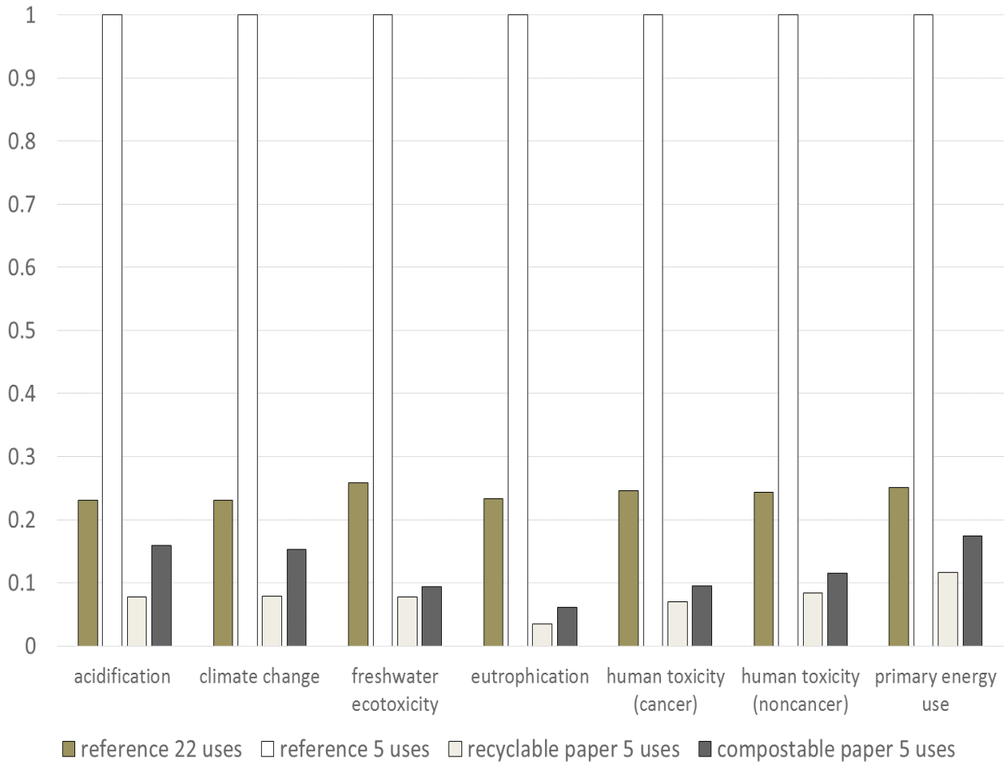
"Compared with garments of the same mass, the extended life garments represent a large improvement in environmental performance over the reference garments, outperforming the reference garments in all effect categories."

Prototype by Professor Rebecca Earley, Center for Circular Design at University of the Arts London

5 impact assessment results and discussion
5.1 short life garments

The relative performance of the short life garment is determined by our selection of a benchmark i.e. the reference short life garment. The number of uses to which this reference garment is put is a central assumption for this LCA assessment. We assume that there is a certain group of consumers who discard serviceable garments after only a few uses. In particular, it is assumed that some consumers are currently discarding the reference garment after 5 uses and putting it in the mixed waste stream. On the other hand, since the national average number of uses for this garment is 22, both values are shown in Figure 5.1. The values have been normalised to the largest value for each effect category.

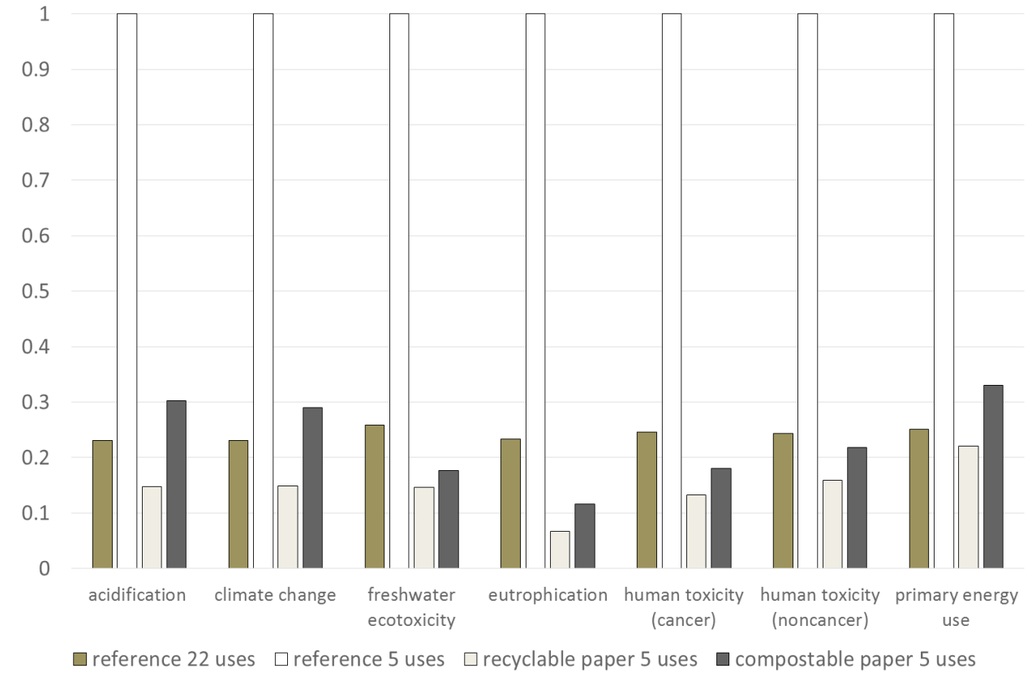
Figure 5.1: Impacts of short life garments, design masses



This figure shows that under these assumptions, the paper-based garments are competitive with the benchmark, with a lower contribution to each of the effect categories shown on the x-axis. The strong influence on the reference garment impacts of its assumed number of uses is also indicated.

The influence of the assumed masses of the short life garments can be illustrated by comparing the outcomes shown in and Figure 5.2. The latter shows the results generated by the LCA if the masses of the paper-based short life garments are increased to match that of the reference garment.

Figure 5.2: Impacts of short life garments, equal masses



In this figure the relative performance of the reference garment and the paper-based garments depends on number of uses to which the reference garment is put and the effect indicator of interest: used 5 times, the relative performance of the reference garment is still much worse than the paper-based garments.

Used 22 times, the reference garment outperforms one or both of the paper-based garments with respect to acidification, climate change and primary energy use, but underperforms in relation to the other four indicators. This outcome shows the importance of keeping the paper-based short life garments light. It also highlights the significance of the assumed number of uses of the garments. This sensitivity is analysed further as described in section 4.6 of this report to generate Figure 5.3 through to Figure 5.6.

Figure 5.3: Contribution to climate change for short life garments

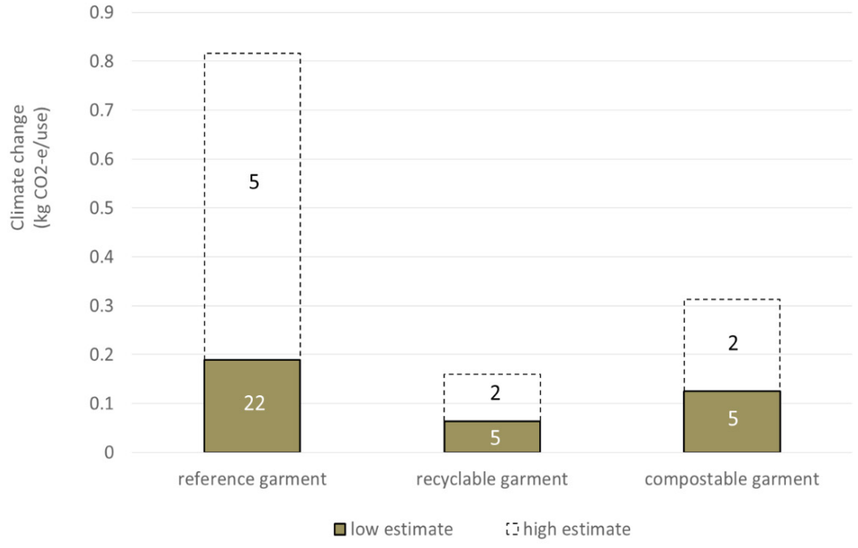


Figure 5.3 indicates that when uncertainties about the use phase of the garments are considered, there may be no meaningful difference between the reference garment and the compostable garment measured by its contribution to climate change. The low and high estimates for the compostable garment are both lower than the reference garment, in the case of the high estimate, by a factor of 60%, all of which suggests improved environmental performance. On the other hand, if the reference garment is used as normal, the uncertainty range associated with the compostable garment straddles the performance of the reference garment. On the other hand, the high and low estimates of the performance of the recyclable garment are both superior to the low estimate of the performance of the reference garment.

Other indicators dominated by energy supply systems show a similar picture to Figure 5.3: acidification potential and primary energy usage favour the recyclable garment over the reference garment irrespective of the use phase assumptions made in this analysis. For these indicators, the lower estimates for both paper garments are superior to the corresponding estimate for the reference garment, while the uncertainty range of the compostable garment straddles the low estimate of the reference garment. Therefore, these indicators are not presented graphically in this report.

The four other indicators show generally favour the paper-based garments more strongly than the reference. Freshwater eutrophication and ecotoxicity potential and the two human toxicity potential indicators (for carcinogenic and non-carcinogenic health effects) favour the recyclable garment over the other two garments. In the case of freshwater ecotoxicity, the difference between the two paper-based garments is relatively small. For the toxicity indicators, the main contributors to the total results for the paper-based garments are the transportation processes in the use phase, and in the case of carcinogenic effects, the production of paper pulp.

Figure 5.4: Freshwater eutrophication potential for short life garments

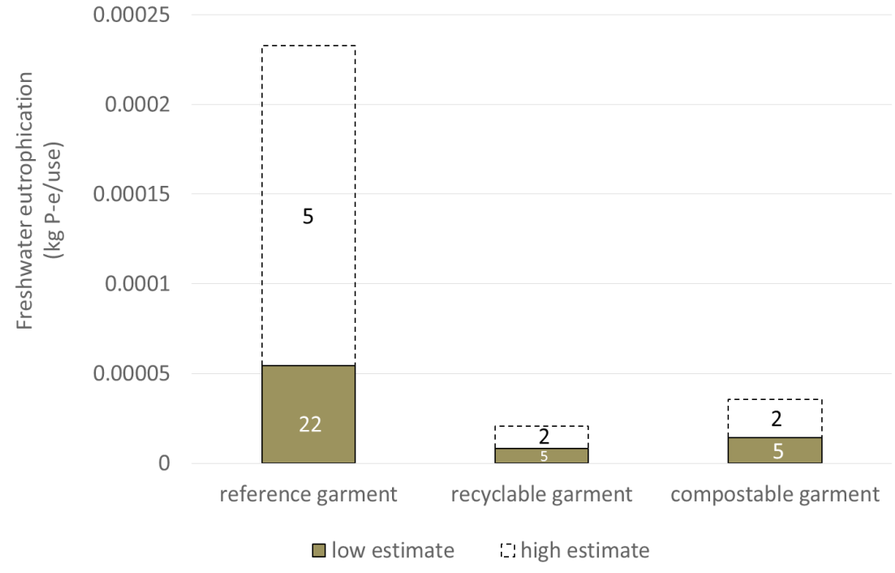


Figure 5.5: Freshwater ecotoxicity potential for short life garments

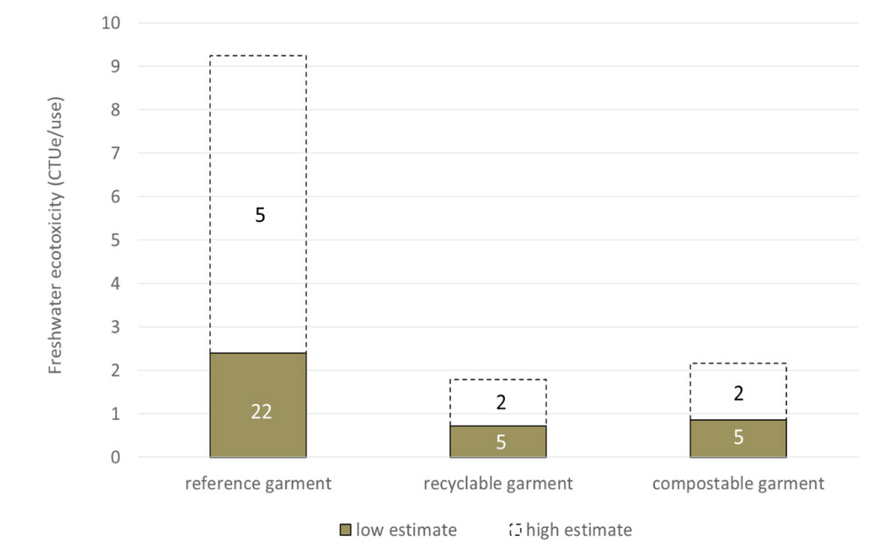
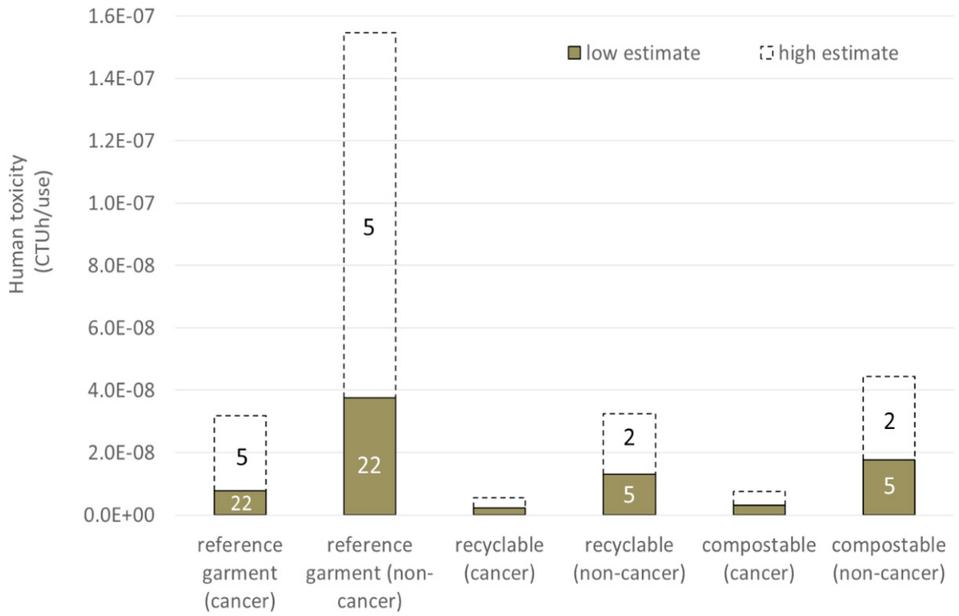


Figure 5.6: Human toxicity potential indicators for short life garments



Overall, these life cycle indicators show that, considered on a per use basis, the short life garments can be environmentally competitive with a conventional garment. However, assumptions about the mass of the garments and the number of times they are used are key variables which can change the outcomes. It should be borne in mind that the typical life span of the reference garment is itself lower than the garment's potential technical life span. As discussed in Section 2.6, the reader should also bear in mind that some uncertainties are built into the model, particularly in relation to the eutrophication, energy demand and toxicity indicators.

One would expect the short life garment materials to be sold under commercial conditions, with financial profit as the underlying goal of business development. Under these conditions, it is to be expected that the owners of the technology will seek to maximise their market, by encouraging behavioural change that favours the purchase of their product. This fact is reflected in the development of today's fast-fashion consumption patterns. Therefore, it is probably unrealistic to assume the paper-based garments will only be sold to people who use a conventional garment 5 times or less. Consequently, an assumption that only consumers who throw out garments after 5 uses will buy the paper-based garments is at risk of invalidation by commercial forces. In other words, consumer behaviour can change.

Users who dispose of the reference garment after 5 uses have the option of donating it to charity and thus increasing the number of times the garment is used up to its typical life span (or beyond). This opportunity does not exist for the short life garment since it is designed for a short life. Therefore, it may be worthwhile limiting the vision for this garment material to situations where either: (1) only a short life span is possible for the garment, or (2) the use phase is associated with much higher impacts than usual. Such a situation may be presented by the hospital sector, where patients undergoing operations do not expect to take garments home, some garments currently in use are designed for brief uses, and the temperatures and bleaching chemicals to which long-life textiles must be exposed during laundry are in excess of domestic norms.

Figure 5.7: Climate change associated with life cycle phases

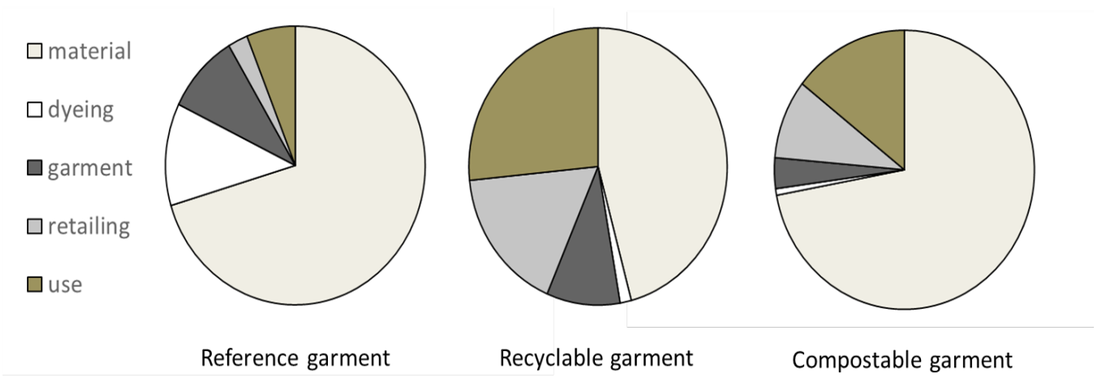


Figure 5.7 shows the relative distribution of contributions to climate change over the different life cycle phases for the short-life garments. (The circles are not sized relative to each other – the relative scales of the climate impacts were shown previously in Figure 5.1, Figure 5.2 and Figure 5.3.) What is most apparent in all cases is that material production (fibre production, spinning and knitting) plays the most important role among the five life cycle phases shown. It should be borne in mind that the majority of this material production impact (57% of it) is associated with the yarn-spinning process according to the analysis in Roos et al (2015).

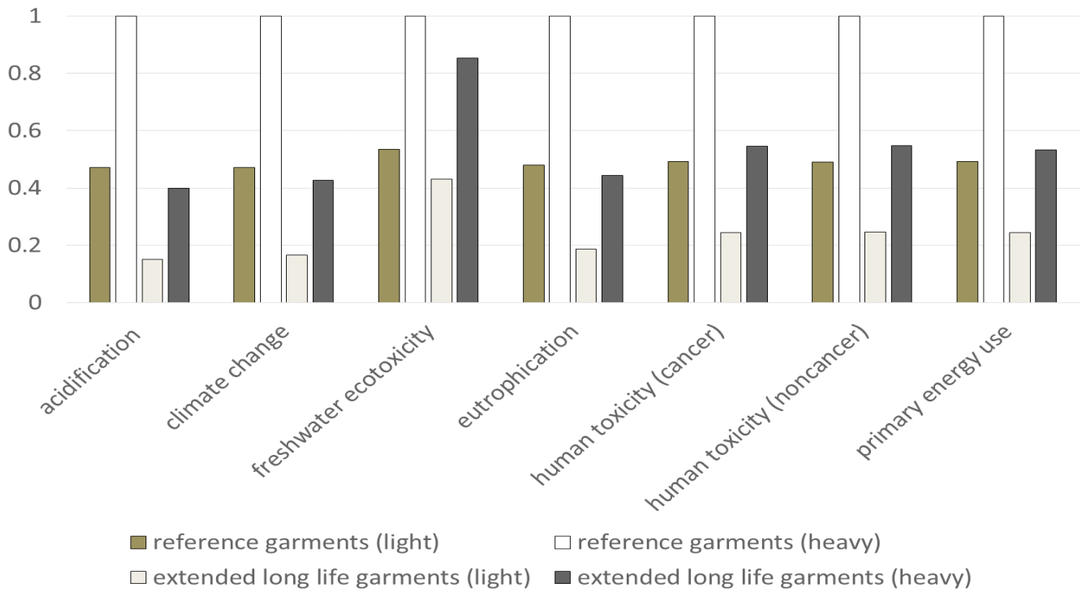
About 16% of the greenhouse emissions from material production for the reference garment are associated with the initial production of the cotton fibre. For the reference garment, dyeing and garment production processes are the next most important. Since each of these is significantly better in absolute terms in the cases of the recyclable and compostable garments, other factors like retailing and use play a larger role. (Note that transportation from the retail environment to the home is included in use.)

About 60% of the use phase impact shown for the reference garment is associated with the transportation of the garment between the retail environment and the home for an average 22-use user phase. The remainder is associated with laundry impacts. These laundry impacts are avoided by the short life garments. Benefits accrued in the end of life ("EoL") phase are not shown here, being negative numbers for the reference and recyclable garments. In those cases, about 5% of the total impact is avoided on account of the replacement of conventional energy supplies through the combustion of the textile waste. There is a very small EoL impact associated with composting of the compostable short life garment (less than 1% of the total) as the benefit associated with avoided peat production are outweighed by the additional consumption of diesel fuel during transportation.

5.2 long life garment

The results of the LCA for the long life garment are summarised in Figure 5.8. As with the short life garments, this indicates the significance of garment weighs in the overall comparison. Compared with garments of the same mass, the extended life garments represent a large improvement in environmental performance over the reference garments, outperforming the reference garments in all effect categories. If the comparison is instead made between heavier garments and garment with the average lighter mass identified in Section 3.3.4, the outcomes are reversed.

Figure 5.8: Overview of LCA results for long life garments



Underlying causes of this are identified using the example of the climate change indicator. This is shown in Figure 5.9 and Figure 5.10 using the same vertical axes and garment masses, so as to aid visual comparison of the effects of extending the garment life. The contributions to climate change show a clear difference between the two garments on a per use basis. Note that the usage data for each cycle of the garments' life was held constant (e.g.: both the conventional garment and the long life garment are used 60 times in the first cycle) in order to facilitate comparison of each garment in the extended cycle with its reference garment. This also indicates the significance of the number of uses, as the proportion of impacts between the different life cycle phases (material production, garment construction, retailing, use and end of life) is roughly constant in the base case (Figure 5.9). This is not surprising considering that each of the garments is synthetic (polyester, or a combination of polyester and polyurethane for cycles 7 and 8), each has to be delivered to a customer, is washed a number of times in proportion to the number of uses, and is disposed. The higher absolute figures for cycles 7 and 8 are predominantly the consequence of the heavier weight of this garment (1.5 kg) compared to the others (0.2 kg).

Since the data in Figure 5.9 are dominated by the material production phase of the garment life cycles, it is logical that the long-life garment performs significantly better in almost all life cycles shown in Figure 5.10. The impact of the sublimation printing steps in cycles 3, 5 and 6 is relatively small (indicated as the garment construction phase in the figure) and similar in scale to the impact of the use phase (customer transport and laundry activities). The principal departure from this observation is cycle 7, in which the performance of the long life garment is almost the same as its benchmark in Figure 5.9. In both cases, the climate change indicator is dominated by the production of the Ultrasuede-type material for the jacket. The part of the garment which the reassembled long life jacket recycles is only 0.2/1.5 = 13% of the total garment mass. On the basis of this data, one apparent way improve the reassembled long life garment in cycle 7 relative to the reference would be to increase the proportion of the garment which is recycled.

Figure 5.9: Contributions to climate change by long life reference garments (values 1-8 refer to cycles in Table 3.2)

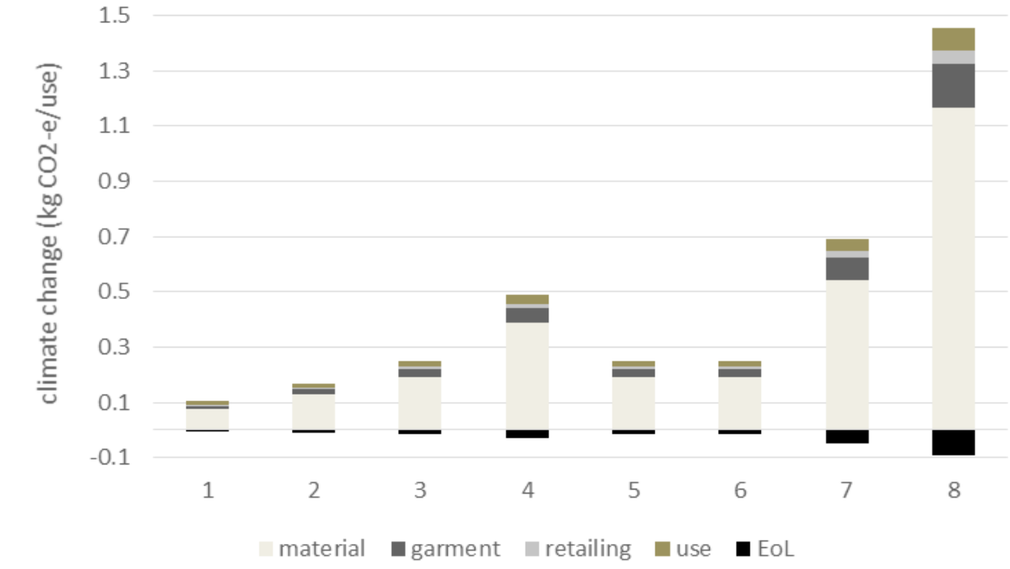
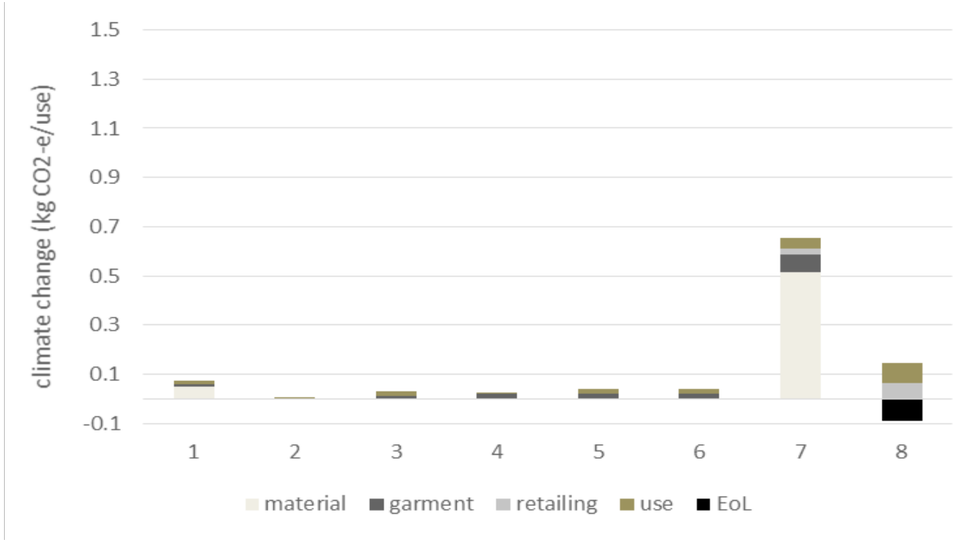
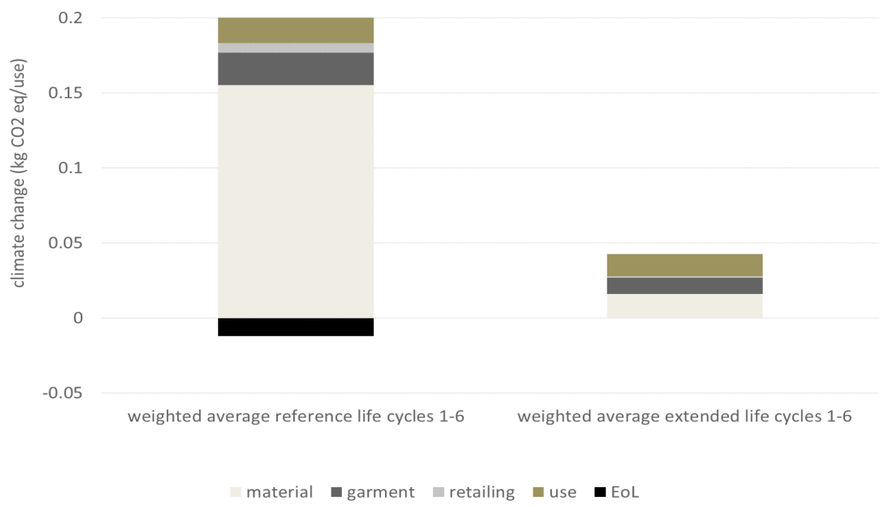


Figure 5.10: Contributions to climate change by extended long life garments (values 1-8 refer to cycles in Table 3.2)



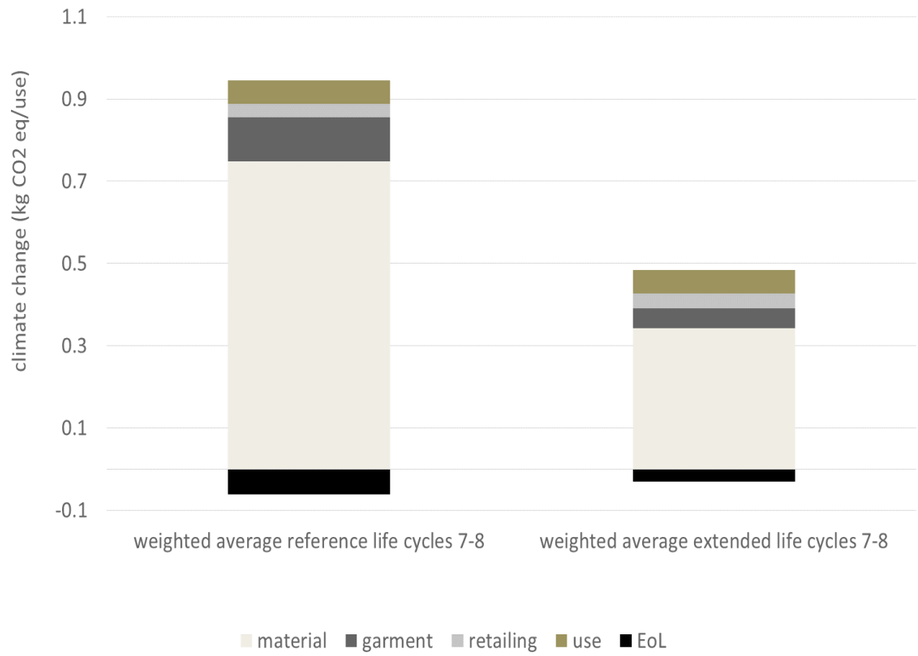
To improve the display of the small bars in Figure 5.10, and considering that this assessment is essentially about two kinds of garment (a blouse and a jacket) the results in this figure and Figure 5.9 are condensed to two averages in Figure 5.11 and Figure 5.12. This indicates that on a per use basis, the impacts of material production are significantly reduced by the multi-printed long life blouse. The impacts of garment production, retailing and use are also reduced, but by a smaller relative amount. No benefit from end of life waste handling are shown for the multi-printed long life blouse, since it becomes the long life jacket shown in Figure 5.12.

Figure 5.11: Average per use climate impacts of long life blouse



The differences between the reference and multi-printed long life jacket shown in Figure 5.12 are primarily that the material production, garment production and end of life impacts are halved due to the necessity of producing only one garment instead of two. While large, this improvement is not as large as in the case of the blouse in Figure 5.11, where one original garment is manufactured instead of six. These results are broadly consistent with previous calculations in the Mistra Future Fashion program, such as those published by Zamani et al (2017). The latter work indicated a greater risk that the transport associated with obtaining garments from the retailer would outweigh the production impacts. This risk is reduced in the present scenario by: (1) the avoidance of retailing between life cycles 1 and 2, and between 3 and 4; (2) the relatively heavy weight of the garments; and (3) the limited number of users compared to some scenarios in Zamani et al (2016).

Figure 5.12: Average per use climate impact of long life jacket



5.3 key manufacturing techniques in the life cycles

In this section we complement the previous discussion of the environmental performance of the garments under study, by examining some of the key textile processes that are included in the manufacturing phase of their life cycles as described in Section 4. We also discuss some of the key uncertainties associated with these processes.

5.3.1 natural dyeing

As indicated by the larger proportion of impacts shown in Figure 5.7 for traditional chemical dyeing, the addition of dye to the pulp ahead of garment manufacturing appears to offer benefits. This is a consequence of the avoidance of additional wet chemistry and drying processes later in the garment manufacturing process. On the other hand it must be remembered that, as indicated in Section 1.1, there is uncertainty surrounding the technical feasibility of this process.

5.3.2 sublimation dye printing

While the multi-printed long life blouse performs very well compared with the reference long life blouse in absolute terms, the proportions in Figure 5.11 indicate that the sublimation dyeing process is a major contributor to the climate impacts of the long life garment scenario. The causes of this are identified below. Figure 5.13 and Figure 5.14 indicate the climate change and ecotoxicity results for the sublimation dyeing process in isolation. Since a relatively small mass of ink is used, the key contributors to the environmental burdens of the process are connected with the production and delivery of the transfer paper (which is assumed to be transported from China) and the energy consumption of the heat press. (Other potential impact indicators are not shown here, but indicate that one or other of these activities is the most important.) Since the paper is ultimately burnt, avoiding other energy production activities, there is a large benefit at the end of life for this material.

Figure 5.13: Contributions to climate change from sublimation dyeing

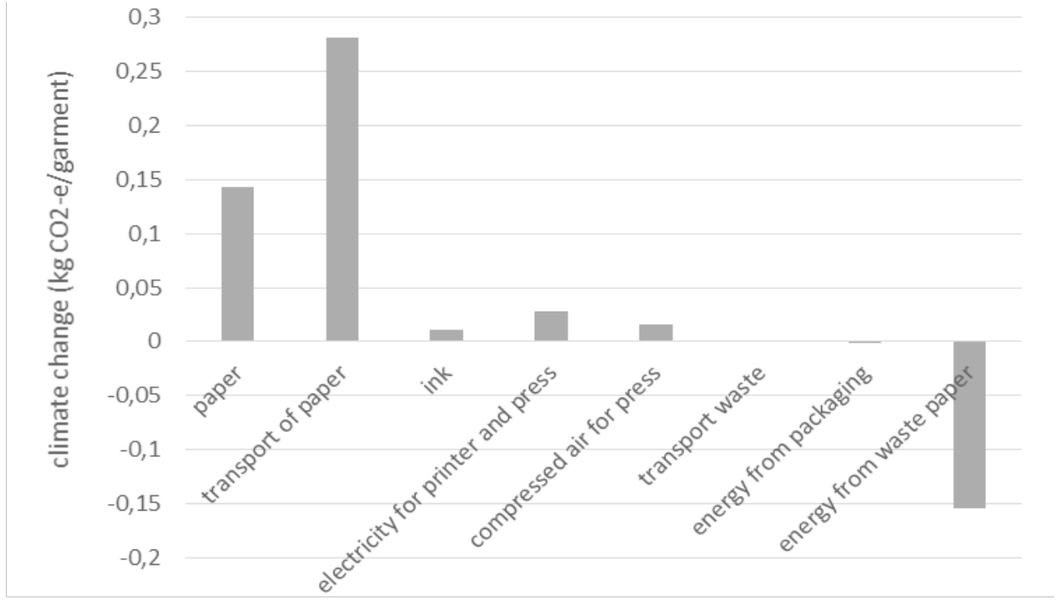
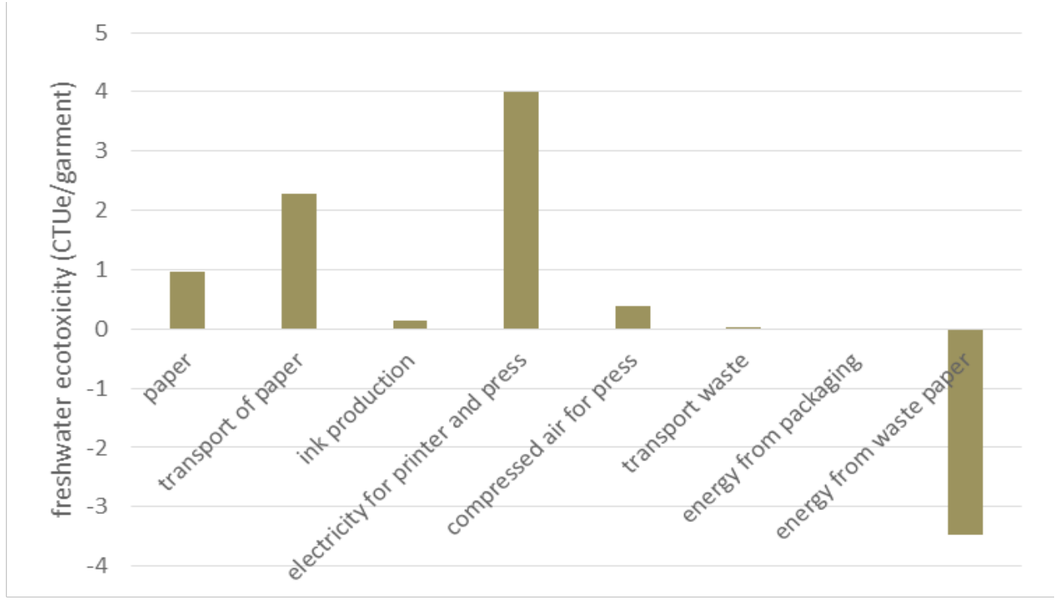


Figure 5.14: Contributions to ecotoxicity from sublimation dyeing (excluding direct emissions from printing and end of life)



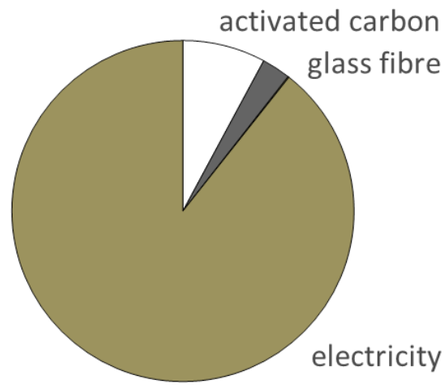
These calculations do not directly address the potential toxicity of the emission of small quantity of ink. As indicated in the inventory, the main constituents of the printer ink are (in descending order) water, glycerol, propylene glycol, TEGMME, proprietary dyestuffs and triethanol amine. However, the production of these ingredients is included.

This report does not aim to provide a comprehensive review of the risks associated with these chemicals, but a brief summary of their applications and hazards is made here. Glycerol is non-toxic and is commonly added to human foods as a humectant, solvent and sweetener. Propylene glycol also has low toxicity – human metabolism converts it to lactic acid, which is a normal blood constituent after human exercise. Propylene glycol is commonly used in antifreeze applications in addition to being a humectant, solvent and preservative in human food. (This is in contrast to ethylene glycol, which is considered less safe due to its child-attracting sweet taste, and its metabolite oxalic acid, which is relatively toxic.) TEGMME is an industrial solvent which is not classified as hazardous in the European Chemicals Agency substance database, but it is suspected to be toxic to reproduction (WHO, 2002). (Its shorter relative diethylene glycol monomethyl ether is listed by EChA as hazardous due to reproductive toxicity.) Triethanol amine has many commercial uses in cleaning and skincare applications. It is listed as an eye irritant (H319). An ingredient in the black sublimation ink (CI Disperse Blue 360) is listed as having the potential to cause allergic skin reactions. It is nevertheless a common dye in textile applications.

It is challenging to assess the range and diversity of information available concerning the relative hazardousness of different chemicals, considering the general incompleteness of many toxicity databases and the opacity of information regarding the dyestuffs in the different printer inks. Epson states that the four colour dye sublimation inks considered in this LCA, when applied to polyester fabrics, pass the requirements of Oeko-Tex Standard 100 for human ecological requirements of Class 1 products for adults, children, and babies up to 36 months. The waste materials and waste garments are assumed to be incinerated in Sweden, a process which will have the effect of destroying any hazardous organic molecules. The main exposure pathways of interest to risk assessors may therefore be during the manufacture of these chemicals and their use in the printing and application process. These environments may give rise to the exposure of workers to compounds in the vapour phase, exposures which are not considered in LCA but which would typically be considered in a quantitative chemical risk assessment. Maintaining containment of ink materials and proper ventilation of the ink production facilities and sublimation printery will be a key element in managing the exposure of workers.

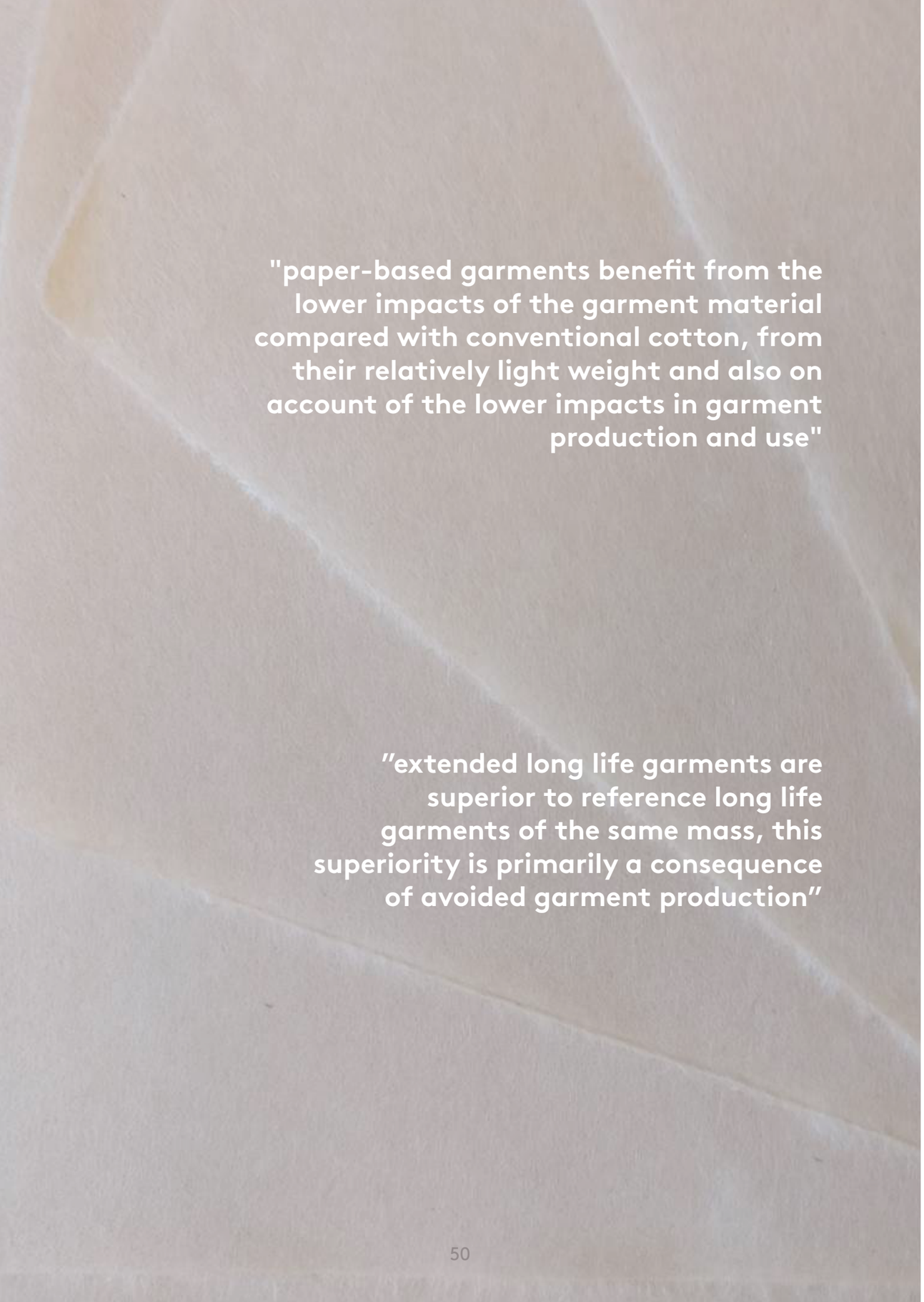
5.3.3 laser cutting

While the equipment used in the laser cutting process is technologically advanced, essentially a focussed light beam is used to burn polyester. The laser light is not particularly powerful, however, being a laser, the light is focussed to a tiny point, giving it the intensity to burn. The main impact of the laser cutting process is caused by the consumption of electricity for the laser cutting table and the air filter, as shown in Figure 5.15.



As indicated in Table 4.2, the air pump for the air filter draws about 38% of the electricity required by the whole laser cutting process. The carbon dioxide lasers typically used for this purpose are not very energy efficient – they convert about 5-10% of the electrical energy into light energy, similar to a traditional, incandescent lightbulb. The combustion process results in some airborne emissions but the particulate matter is assumed to be arrested by the glass and activated carbon filter. Given their mixed materials, the ultimate disposal of the filter units will presumably be to landfill, but this has not been modelled here. In any case since we assume the activated carbon is produced from wood-based charcoal, degradation or combustion will not lead to an increase in non-biogenic carbon dioxide emissions.

On the other hand, the polyester combusted in this process was also excluded from the calculations and could potentially increase the contribution to climate change. Evaluating this potential requires some assumptions as it is not known how much of the 1.3 kg Ultrasuede-type polymeric material will be burnt by the laser, but assuming it is 1% (13 g), this would represent 30 g of carbon dioxide per garment. This is approximately 15% of total value on which Figure 5.15 is based (204 g/garment) or only 0.5 g of 653 g CO2-e/ use over the whole of life cycle 7. As a relatively insignificant and uncertain emission this potential element of the life cycle inventory was not pursued further.



6 conclusions

This report assessed short and long life garment scenarios defined during the Mistra Future Fashion program. The aim was to find out if certain prototyped garments represent environmental improvements over reference garments, and what factors are the most significant in controlling their environmental impacts. Life cycle assessment was applied using the use of a garment (i.e. wearing it for a day) as the functional unit. As a starting point, short life garments were assumed to be used five times before disposal. On the other hand the long life garments were assumed to be used as a blouse 180 times over 15 years, and after conversion to a jacket, a further 90 times over a further 15 years. These use patterns represent a variation on average consumer behaviour for the garment classes used by the Statistics Sweden but are interesting starting points for illustrating alternatives in garment design.

The paper-based short life garments considered in this assessment are competitive with their reference benchmark garment (a cotton t-shirt) and superior if we make the assumption that the consumer would throw away the reference garment (i.e. in the garbage) after five uses. The recyclable garment appears to be superior to the compostable garment. These paper-based garments benefit from the lower impacts of the garment material (fibre production, spinning and knitting) compared with conventional cotton, from their relatively light weight and also on account of the lower impacts in garment production and use. If the paper-based garments are made at the same weight as the reference garment, and the reference garment is donated to charity or otherwise used for a typical lifespan, the paper-based short life garments may be inferior to the reference garment with respect to some of the environmental effects assessed in this study.

The extended long life garments considered in this assessment are superior to reference long life garments of the same mass according to this assessment. This superiority is primarily a consequence of avoided garment production via reprinting and reassembly of the initial garment to extend its useful life. The environmental impacts associated with sublimation dye reprinting and laser cutting do not significantly impact the overall environmental performance of the long life garments. Some constituents of the dyes are regarded as proprietary information, and could not be included in this assessment. Epsom claims Oeko-tex certification for them when applied to polyester, although for the Disperse Blue 360, a warning statement was issued by the European Chemicals Agency (ECHA) for Disperse Blue 360 in relation to the risk for allergic skin reactions. This is only discussed qualitatively in this life cycle assessment.

The scenarios presented in this report are essentially explorative rather than attempts to model an existing business or behavioural pattern. The reader should therefore take care not be take them out of the present context when interpreting the results.

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8 Appendix 1 – description of impact categories

Descriptions about the included impact categories shown below are taken from Roos et al. (2015), with some minor modifications.

8.1 climate change

Climate change refers to the consequences of increased average temperatures of the earth's atmosphere and oceans. This increase is mainly because of emissions of greenhouse gases such as carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O) and chlorofluorocarbons (CFCs) from anthropogenic sources such as the combustion of fossil fuels and deforestation (IPCC 2013).

For characterising climate impact, in this report we used the Global Warming Potential (GWP) with a 100 year perspective (GWP100) expressed in kg CO2 equivalents (IPCC 2013), and assumed that biogenic CO2 emissions are climate neutral. The latter assumption presumes that within relevant spatial system boundaries (e.g. at a landscape or national level) or within a reasonable time horizon (e.g. within one rotation period: the time period from harvest to harvest), the forestry or agriculture that generates the extracted biomass is carbon neutral. This means that the land management practices ensure that as much carbon is sequestered (above and below ground) as is harvested. In other words, the land is sustainably used with regard to carbon extraction.

8.2 acidification

Precipitation (rain, snow, fog, etc.) deposit acidifying substances from anthropogenic sources (e.g. sulphur dioxide (SO2) and nitrogen oxides (NOX) released in combustion) to terrestrial and aquatic ecosystems which may increase pH levels (the concentration of hydrogen ions, H+). This may damage freshwater and coastal ecosystems and soils, with consequences such as forest decline, increased fish mortality and damages to buildings (Guinée et al., 2002). Also, heavy metals released due to increased pH levels can damage freshwater resources. For characterising acidification impact, we used the accumulated exceedance method developed by Seppälä et al. (2006), with characterisation factors expressed as mole H+ equivalents.

8.3 freshwater eutrophication

Nutrients like phosphorus (P) or nitrogen (N) released to freshwater systems may cause increased biological productivity, such as production of planktonic algae. The algae sink to the bottom and are broken down with consumption of oxygen in the bottom layers, causing a dead environment and (among others) increased fish mortality. The most significant sources of nutrient enrichment are the agricultural use of fertilizers, the emissions of nitrogen oxides from combustion and wastewater from households and industry. For characterising freshwater eutrophication impact, we used the EUTREND model method developed by Struijs et al. (2009), with characterisation factors expressed as kg P equivalents.

8.4 photochemical ozone formation

Increased levels of ozone at ground level arise through the reaction of volatile organic compounds (VOCs), for example ethene, with oxygen compounds or oxides of nitrogen in air and under the influence of sunlight, so called photochemical oxidation. The effects on human health are, amongst others, irritation of eyes and mucous membranes as well as impaired respiratory function. Ground level ozone also has severe effects on vegetation, resulting in agricultural production losses (Guinée et al. 2002). For characterising photochemical ozone formation, we used the LOTOS-EUROS model with characterisation factors expressed as kg NMVOC equivalents (Van Zelm et al. 2008).

8.5 freshwater depletion

The use of freshwater in water-scarce areas can cause water depletion with numerous environmental impacts, including effects on aquatic organisms and terrestrial ecosystems as well as malnutrition among humans (Pfister et al. 2011). For characterising water use, we used the Swiss Ecoscarcity (Frischknecht and Knöpfel 2013) method recommended by ILCD (European Commission 2012). This method accounts for consumptive water use, which is water embodied in products, water evaporated due to plants or industrial processes, and water extracted from one water catchment and released to another. In terms of the LCI inventory, this is lake water, river water and rain water used in the product system, minus water returning from the product system to natural systems, e.g. waste water, cooling water and turbine water. The method multiplies the amount of consumptive water use with a country-specific weighting factor accounting for water scarcity. This is not done automatically within the LCA software used in the present study, and as it is not feasible to identify the country of location for all background processes. Therefore, we have manually applied country-specific weighting factors for the major flows of consumptive water use only (thus, the remaining flows are implicitly assigned a scarcity factor of 1). The tables below show the weighting factors used for the jeans and t-shirt, respectively.

8.6 toxicity

The toxicity has been evaluated with the LCA method USEtox (Rosenbaum et al. 2008), which is the recommended method by European Commission (2012). USEtox calculates characterization factors for human toxicity and freshwater ecotoxicity at midpoint level. USEtox uses the unit CTU (Comparative Toxic Unit) which is an indirect measure of the number of cases per year caused by toxic effects.

The ILCD handbook (European Commission 2012) recommends that the LCA practitioner should complement the methods with missing characterisation factors if they can have impact on the results. This can be done for processes that are modelled within a project but it is impossible to compensate for missing data in database data.

The characterization factor for human toxicity impacts (human toxicity potential) is expressed in comparative toxic units (CTUh), and is the estimated increase in morbidity in the total human population, per unit mass of a chemical emitted, assuming equal weighting between cancer and non-cancer due to a lack of more precise insights into this issue. The result is calculated as [CTUh per kg emitted] = [disease cases per kg emitted]. All cases of non-mortal human toxicity impacts, which do not lead to death but to disability and illness, are weighted against their relative severity compared to death.

The characterization factor for freshwater ecotoxicity impacts (ecotoxicity potential) is expressed in comparative toxic units (CTUe), and is an estimate of the potentially affected fraction of species (PAF) integrated over time and volume, per unit mass of a chemical emitted. The result is calculated as [CTUe per kg emitted] = [PAF × m^3 × day per kg emitted].

One CTUe thus equals one cubic meter of freshwater where the species in the ecosystem are exposed daily to a concentration above their no-observed effect concentration (NOEC). An environmental concentration is considered to present an acceptable risk if not more than 5% of all species is exposed above their NOEC.

Mistra Future Fashion is a research program that focuses on how to turn today's fashion industry and consumer habits toward sustainable fashion and behavior. Guided by the principles of the circular economy model, the program operates cross disciplinary and involves 60+ partners from the fashion ecosystem. Its unique system perspective combines new methods for design, production, use and recycling with relevant aspects such as new business models, policies, consumer science, life-cycle-assessments, system analysis, chemistry, engineering etc.

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