TEKSTIL REVOLUTIONEN

LIFE CYCLE ASSESSMENT OF 5 T-SHIRTS

ID® IDENTITY

February 2023

Life Cycle Assessment of 5 t-shirts Produced by

ID® IDENTITY

T-shirts 0300, 0370, 0510, 0552, 0552b

PRODUCED BY

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TÆNKETANKEN TEKSTILREVOLUTIONEN

Tekstilrevolutionen is a thinktank with a focus on textile industries that pushes the industry towards a positive impacts on the planet and the people inhabiting it. Tekstilrevolutionen works with sustainability-ambitious brands and actors in the textile industry, supporting them in their efforts to become part of the textile industry of the future.

Website: https://www.tekstilrevolutionen.dk/
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DISCLAIMER

The results and conclusions are related to specific contexts, assumptions and methodologies described in the report. Therefore, they should be used in their entirety. They should not be taken out of their context and should not be compared to other assessments or to industry benchmark.

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TECHNICAL SUMMARY

This Life Cycle Assessment study focuses on the environmental impacts of 5 t-shirts, in which one out of 5 is a hypothetical scenario. The t-shirts are made of the following material compositions:

- T-shirt 0300: 40% Virgin polyester - 60% Better Cotton cotton
- T-shirt 0370 (Ecolabelled): 40% Recycled polyester - 60% Better Cotton cotton
- T-shirt 0510: 100% Conventional cotton
- T-shirt 0552: 100% Organic cotton
- T-shirt 0552b: 100% Better Cotton cotton (hypothetical scenario)

These products are produced by the commissioner, who is ID® IDENTITY. The impact is analysed over a range of impact categories; among those, Climate Impact, Water Scarcity, Ecotoxicity, Eutrophication, and Human Health can be mentioned.

Based on ISO 14040/44, this LCA follows the main steps namely: Goal definition, Scope definition, Life Cycle Inventory, Life Cycle Impact Assessment, Life Cycle Interpretation. As part of Life Cycle Impact Assessment Characterisation, Sensitivity and Uncertainty analysis, Normalisation (Optional), and Weighting (Optional) are included as part of the analysis.

Purpose. To assist the commissioner a support tool for making decisions from an environmental standpoint for when designing a new product, as well as understanding the environmental performance of the current products.
Moreover, the result of this study will help other departments such as Purchase and Sales Departments, as well as communicate with the customers.
Lastly, to have transparent communication with suppliers.

This purpose is done by the choice and application of different methodologies.

Methodology. The modelling approach in the study is consequential, assessing the life cycle stages from cradle-to-grave, considering the system expansion as multifunctional process handling. The data sources used primarily for the analyses come from the commissioner and their suppliers, with additional data from the ecoinvent database, and the academic literature. The impact assessment method and database used is ReCiPe 2016 and the ecoinvent database 3.9 in SimaPro software (3.6 as to consequential-unit processes), respectively for 18 midpoint and 3 endpoint impact categories. In addition, the AWARE single impact assessment for assessing the environmental impact on Water Scarcity category.

Receiving these data and choosing these methods provides us with a variety of results.

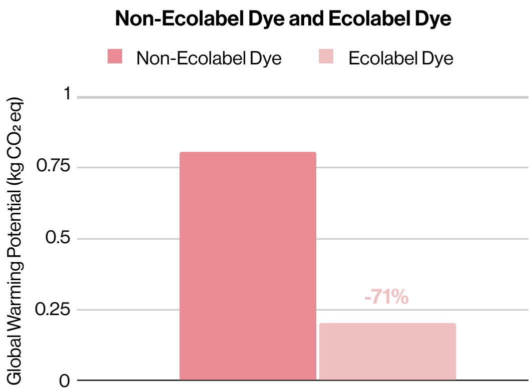
Result. Overally, the results indicate that depending on the t-shirts composition, they can contribute differently on the environmental impact categories. While normalised results show that t-shirt 0552 performs generally the best, characterised results indicate that this t-shirt has the highest impact on the Mineral Resource Scarcity category.

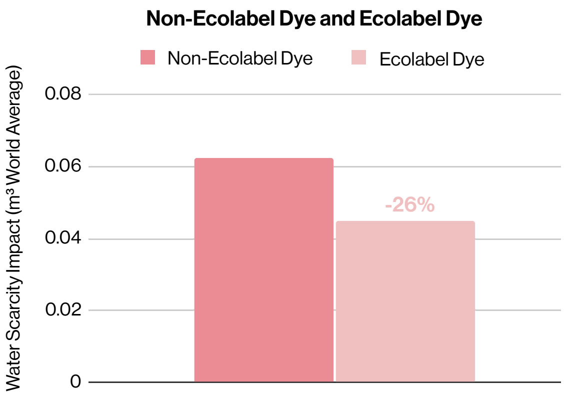
The results derived from 2 different weighting methodologies shows that all t-shirts could negatively impact Terrestrial Toxicity, Agricultural Occupation, Land Use, and Freshwater Ecotoxicity.

Uncertainty analysis results vary from one impact category to another, depending on the t-shirts composition.

A comparison between 2 different approaches of dyeing on Global Warming Potential and Water Scarcity impact categories is conducted: Ecolabel dye (t-shirt 0370) with non-Ecolabel dye (t-shirt 0300).

The result shows that the Ecolabel dyeing process shows an over 70% environmental burden reduction in the Global Warming Potential category compared to the non-Ecolabel dye. It also decreased the environmental impact of the Water Scarcity impact category by 26%.



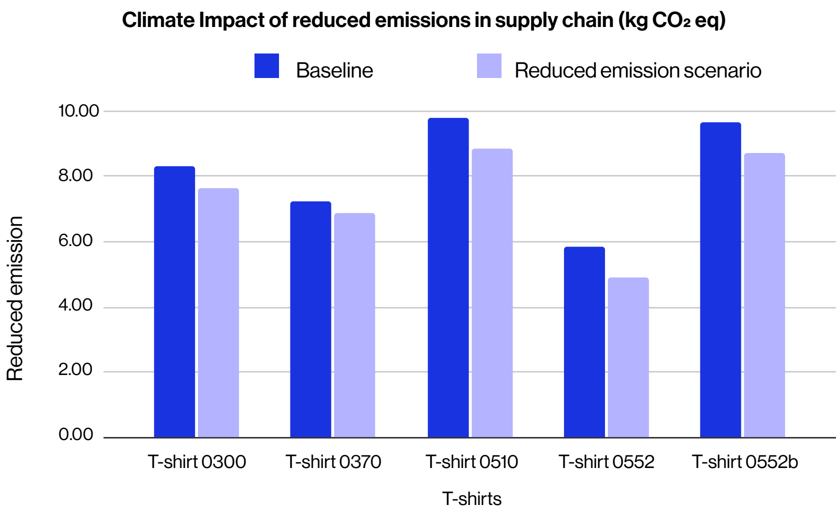


These are significant reductions depending on the impact category. This rule applies also when analysing the Hotspot of the t-shirts products. This analysis is done on 6 different impact categories, chosen by ID® IDENTITY.

The categories are Global Warming Potential, Freshwater Eutrophication, Land Use, Freshwater Ecotoxicity, Water Consumption and Water Scarcity; interestingly, fibre extraction stage and the use stage of the t-shirts, have high environmental impacts on all of the mentioned impact categories compared to the other stages. The exception is in t-shirt 0552 in the fibre extraction stage on Global Warming Potential which shows a positive environmental contribution. This is explained as this study follows the consequential modelling, running a process contribution indicates that due to more demand for planting cotton, less field for planting soybean seeds is needed (-92.5 %).

Moreover, a scenario is created indicating the environmental impact reduction when replacing fossil fuel-based energy to renewable sources during the Cut-Make-Trim stage - at the factory site.

The result shows an overall improvement in the Climate Impact from all the t-shirts.



These results are followed by recommendations and future works.

Recommendation. The study provides recommendations based on the result that covers different aspects. It is recommended to increase the engagement with laundries by obtaining more information on the end-of-life for more in-depth analysis. Also, it suggests more communication with end-users to collect more information on how the t-shirts are benign used and also how this could impact the environment. Suppliers are the other target group that is recommended to motivate them for greener facilities. Connection at the farm level could also ease the data collection and increase the traceability of the supply chain, and more.

EXECUTIVE SUMMARY

This Life Cycle Assessment study focuses on the environmental impacts of 5 t-shirts, in which one out of 5 is a hypothetical scenario. The t-shirts are made of the following material compositions:

- T-shirt 0300: 40% Virgin polyester- 60% Better Cotton cotton
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- T-shirt 0510: 100% Conventional cotton
- T-shirt 0552: 100% Organic cotton
- T-shirt 0552b: 100% Better Cotton cotton (hypothetical scenario)

These products are produced by the commissioner, who is ID® IDENTITY. The impact is analysed over a range of environmental impact categories such as Climate Impact, Water Scarcity, Ecotoxicity, Eutrophication and Human Health.

Based on ISO 14040/44, LCA has the main steps which are Goal and Scope definition, Life Cycle Inventory, Life Cycle Impact Assessment and Life Cycle Interpretation. Life Cycle Impact Assessment includes Characterisation, Sensitivity and Uncertainty analysis, Normalisation, and Weighting; the last two are optional.

The purpose of this study apart from understanding the environmental impact of the current products is to assist the commissioner not only on making decisions from an environmental point of view, but also helping with designing a new product. In addition, the result of this report provides transparent communication with suppliers. For this purpose the modelling approach of consequential is chosen, to assess the life cycle stages from cradle-to-grave. The data sources used primarily for the analyses come from the commissioner and their suppliers. To cover the missing data, other sources such as ecoinvent database, and the academic literature are used.

T-shirts' environmental performance are examined on different environmental impact categories: 18 midpoint and 3 endpoint impact categories. To assess the impact on water scarcity, in addition, the AWARE single method is chosen.

The findings of the study is that t-shirts' composition can affect their environmental performance in different categories. The use and fibre extraction stages were found to have the highest environmental impact in several categories. The use of eco-label dye showed a significant reduction in environmental burden in Global Warming Potential and Water Scarcity categories. Additionally, replacing fossil fuel-based energy with renewable sources during the Cut-Make-Trim stage was found to improve the climate impact of all the shirts.

The study recommends increasing the engagement with laundries to obtain more information on the end-of-life of t-shirts which leads to in-depth analyses. It also suggests more communication with end-users to collect more information on the use of t-shirts. The involvement of suppliers and other target groups such as farmers are also important as they can ease the data collection and increase the traceability of the supply chain.

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INTRODUCTION

This section introduces what a Life Cycle Assessment is, who ID® IDENTITY is, as well as the technical terms.

WHAT IS LIFE CYCLE ASSESSMENT?

Life Cycle Assessment (LCA) is a tool to measure the environmental impacts arising from the life cycle of a product, a process or a service. This means that it is not only measuring a single footprint element such as carbon dioxide (CO_2), but also it takes into account other influential impacts from Land Use, Water Consumption, Mineral Scarcity and Chemical pollution. You can see the list of all the impact categories in Appendix C. The LCA is defined based on the function that a product or a service delivers, rather than the product itself. This means that how well or for how long a product or a service will fulfil its purpose is relevant.

Most LCAs follow the ISO 14040/44 standards, which include the principles and framework of how to conduct an LCA, as well as provide its requirements and guidelines. Yet, the data and the choices of processes for analysis are always based on assumptions and methodological choices. The LCA we present in this report is no exception. Assumptions shape the final results of the LCA, and the ones made in this report include *'how many times a product is used by the end user', 'how it is taken care of',* and *'what type of transportation is being used'*. Besides, the types of databases and calculation programs that have been used also have a say.

The assumptions will be described along the way throughout the report, and an extensive list of assumptions can be found in Appendix D. Moreover, methodological choices are also influencing the final results which will be explained and discussed throughout the report. This means that one should be considering what assumptions and methods have been used in the application of an LCA when attempting to compare results from one LCA to another.

WHO IS ID® IDENTITY?

This study is conducted for the company ID® IDENTITY who is also the commissioner of this study. ID® IDENTITY, is designing many various Corporate Wear styles with quality for companies and events. They introduce their products as long-lasting which is due to their unique design that will not go out of fashion. In addition, the same style could be ordered for as many years as needed.

ID® IDENTITY describes their DNA which has a root structure as

- Designing based on the functionality and durability of the clothes during their USE
- Choosing the best materials considering the environment for the CARE
- Creating harmony to UNITE people

ID® IDENTITY has the ambition of speeding up their green transition. They already have 100% of their electricity purchase powered by Danish wind power which is a renewable CO2-neutral energy source (ID® IDENTITY, no date-a). They primarily work with 6 out of 17 Sustainable Development Goals. Also, they have reduced the production of their materials made of paper, as well as their waste generation to 37% and more than 12%, respectively. This company is also a member of Better Cotton Initiative (BCI) which helps them to achieve their commitment to source their cotton responsibly by 25% by 2030. (ID® IDENTITY, no date-b).

TECHNICAL TERMS

Commissioner	The commissioner is the person or organisation that has requested the LCA study. In this case, this is ID® IDENTITY.
Foreground and background system	The foreground system is the part of the system that is specific to the product being studied, whereas the background system is the part of the system that is not specific to the product being studied. For example, the specific dyeing or knitting techniques are both in the foreground system, but the extraction of crude oil for making polyester is in the background system. The foreground and background system of this study is shown in Figures 3 to 7.
System boundary	Based on ISO 14040/14044, the system boundary is framing the scope of the study. The system boundary is always explained to get a clear picture of which parts of the system are included and which are excluded. The system boundary of this study is shown in Figures 3 to 7.

Environment/product system	Generally speaking, the Ecosphere is "the nature", whereas the Technosphere is "the society". These terms are useful to explain the interaction of the modelled system with the surroundings. For example, some processes will emit gases into the atmosphere - the Ecosphere. Other processes might cause changes in the society - such as energy generation from the incineration of a product.
Functional unit	Instead of focusing on a product, the analysis measures the environmental impacts of fulfilling a specific function or functions of the product. This way, different solutions for fulfilling the need can be compared. In general, the functional unit has to state a function and cover the answer to the *"What?, How much? or How many times?, When?, How well?, and for How long?*". The functional unit of this project is described under the *Object of the assessment and functional unit.*
Reference flow	The reference flow is provided to define the amount of the needed service, product or process to fulfil the functional unit. This varies for different services, products or processes, since a product might have been made of different materials, and thus have different lifespans. The reference flows of this project are described under the *Object of the assessment and functional unit.*
Product Environmental Footprint	An initiative initiated by the EU to streamline environmental measurement for various categories. Currently, the Product Environmental Footprint (PEF) regarding textile products is not finished, but some elements have been used to guide this study. Home page: https://ec.europa.eu/environment/eussd/smgp/ef_pilots.html
International Reference Life Cycle Data System	International Reference Life Cycle Data System (ILCD) provides general guidelines for LCA. It is no longer being updated and is considered obsolete. Yet, to describe the decision context of the LCA, it is being used. Home page: https://eplca.jrc.ec.europa.eu/ilcd.html

GOAL DEFINITION

This section presents the goal definition of the study.

In this section, the goal of the study will be explained, as well as descriptions of how the study will be used and by whom.

INTENDED APPLICATION

This study has 3 desired outcomes:

1. This study intends to assist the commissioner of the study in decision-making regarding the design of new products, the improvements of the current ones, as well as overall environmental improvements to their system and processes. This will be done through a hot-spot identification which indicates the life cycle stages with the highest environmental impacts compared to other stages.

2. Another intention of this study is to assist decision-making in the Purchase and Sales Departments, where information regarding the costs of products and materials are compared to environmental burdens.

3. The results of this study are intended to be published through the commissioner's channels as they wish to have transparent communications.

***Figure 1**. T-shirts under study. From left to right they are 0300, 0370, 0510 and 0552. As t-shirt 552b is a scenario, the visualisation is not included.* Image is taken from ID® IDENTITY website (ID® IDENTITY, no date-c).

This study will examine the environmental footprint of 5 different t-shirts, in which 1 is not currently in production and is instead treated as a scenario. The t-shirts are coded 0300, 0370, 0510, 0522, and 0552b (scenario). All t-shirts are created by the commissioner, using the same functional unit, but the different material compositions and origins.

LIMITATIONS DUE TO METHODOLOGICAL CHOICES

The study evaluates 18 impact categories at the midpoint level, 3 damage categories at the endpoint level, and 1 impact category focusing on Water Scarcity. However, these categories did not cover all environmental aspects, due to a lack of data and methodological limitations. The field of Life Cycle Assessment has only relatively recently begun to approach the issue of plastic waste, both in terms of required life cycle inventories and appropriate Life Cycle Impact Assessment models (Verones et al., 2022) Microplastic pollution, for instance, is a type of impact category which is not included in this analysis. Other impacts outside the scope of the environmental realm, i.e. social sustainability and economic effects, are also not included. (Ejrnæs, et. al. 2021; Biodiversitetsrådet, 2022; COP15, 2022; Convention on Biological Diversity, 2022; Verden Skove, n.d.)

Since the studied t-shirts are designed specifically for a professional context - where optimising for the lifetime of the products is a selling point - perspectives on the t-shirts for private use should be drawn with caution; since the t-shirts studied here, are made with a focus on giving them a long active lifespan, and they are made to be able to endure industrial laundry. T-shirts made for private use are likely to be used much fewer times and designed for different laundry conditions.

DECISION CONTEXT AND REASONS FOR CARRYING OUT THE STUDY

The approach in this study is consequential, however, a sensitivity analysis is done by attributional approach. This follows the ILCD guidelines.

Considering the goal of this study which is helping the commissioner with decision-making and transparent communication, the context is decided to be *decision context A (Micro-level decision support)*. This means that no structural changes (such as the construction of new power plants) would take place based on the result of this study.

TARGET AUDIENCE

The report has two groups of audience:

- The primary target audience of the study is the commissioner (specifically the Sales, Purchase, Design and Leadership Departments) and its stakeholders. Some of these will have little prior experience in environmental reporting, many, however, will not have any experience in this field.
- The general public will be the secondary audience with no prior experience in environmental assessments.

The latter will influence how the report is written and how technical terms are explained. Please see the *Abbreviations and technical terms* for a brief introduction to the key concepts.

DISCLOSURE TO THE PUBLIC AND CRITICAL REVIEW

As explained earlier, the intention of this study is to calculate the environmental performance of the 5 t-shirts and assess their environmental performance during entire life cycles.

The study is intended to be publicly available, hence a critical review is being provided. The critical review is conducted as a third-party review (comparable to a peer review in academia) by an external expert that has not been involved in the study.
The purpose of a critical review is to assure the quality of the study, that assumptions are realistic and to improve credibility.

The review is made in a concurrent manner rather than at the end of the study. This assures a higher quality since corrections can be made along the way.

The Critical Review Statement can be found in Appendix K.

The comparison between the 5 t-shirts is intended to be fair, and the requirements for comparative studies are met. Such requirements include identical functional units, the same data quality, and the same structure for the system boundary.

For comparative assertion, however, the study should go through a panel of experts. This report is not qualified for such an assertion.

COMMISSIONER OF THE STUDY AND OTHER INFLUENTIAL ACTORS

The commissioner of the study is ID® IDENTITY (REXHOLM A/S) who also financed the study.

Tænketanken Tekstilrevolutionen is the organisation conducting the LCA study.
Since the information from all investigated products in the study is provided by the commissioner, limitations with comparing up-to-date data with generic or old data are avoided. As the commissioner had access to rich and up-to-date information, there was limited need for using generic data.

The study will go through a concurrent critical review by an LCA expert with experience in the field of textiles and apparel.

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SCOPE DEFINITION

In this section, the scope of the study will be explained.

In this section, the scope of the study will be explained, as well as the system boundary, handling of the processes, and data specificity.

DELIVERABLES

The study has two formal deliverables which are mandatory:

- Life Cycle Inventory (LCI) of the 5 t-shirts which indicates the dimension of the collected data, and the relevant calculations.
- Life Cycle Impact Assessment (LCIA) which interpret the results of the analysis.

As optional steps in LCA we include Normalisation and Weighting.

Normalisation will be conducted to indicate the magnitude of the environmental burden of the 5 t-shirts. The normalisation factor is often a year in an average person's life. It also will give a point of reference for observers of the study who are unfamiliar with the LCAs and the typical environmental impacts.

Weighting is included to give an overall grade of the products but rather, understand the partial impacts. Therefore, it shows the importance of the environmental impact on the category. The two chosen methods for weighting are the Environmental Prices and the EF 3.0 Method (adapted for SimaPro substances) version 1.03.

The present study also takes into account both the use stage and end-of-life. The functional unit is therefore defined as meeting a need for the end-user (read more about this later). This means that the longevity of the product is considered.

OBJECT OF THE ASSESSMENT AND FUNCTIONAL UNIT

The functional unit is the central measurement in this study. It provides the comparability of the life cycles of the 5 t-shirts to each other. The life cycles will be scaled to fit the functional unit.

The functional unit is based on the obligatory properties of a product; meaning that the t-shirts naturally have several functions. Some of these are obligatory while others are added benefits (positioning properties). Table 1 shows a list of properties of the t-shirts, defined as either obligatory or positioning (Hauschild, et. al., 2018).

Table 1. *Obligatory and positioning properties of 5 t-shirts.*

Obligatory properties	Positioning properties
Cover male torso size large	Affordable price
Washable in industrial laundry systems without changing shape or colour (200 times of washing - Please see Table 7)	Lower environmental damage Comfort
Compliance with the EU and national regulations (eg. REACH).	Availability of colours

The functional unit has been defined as:
"Provide coverage of large size male torso, for 8 hours of non-intensive activities, for 200 days of wearing."*

*The size large (L) is defined in Table 2 below for each t-shirt (full overview in Appendix X1 to X4).

Table 2. *The description of the size large for each existing t-shirt.*

Size L	0300	0370	0510	0552	Unit
1.2 chest width	56	56	56	56	cm
Front length from hps	75	75	75	74	
Shoulder to shoulder	52	48	52	47	
Sleeve length	21.5	22	21.5	23.5	
½ upper arm width	25	21	24	21	

REFERENCE FLOWS

The reference flow is defined by the ISO 14044 as "[...] the measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit.". In other words, the reference flow indicates "how much" of the product system's output that is needed to fulfil the functional unit. For this study it can be described as:

States on how many of the life cycles of a specific t-shirt are needed to fulfil the functional unit (of 200 washing times).

In this case, the reference flow for each t-shirt's life cycle is defined through the average number of washing cycles for a t-shirt before the end of its active life.

Below in Table 3, the reference flow for each t-shirt is provided. The company provides the estimated life time of the:

***Table 3**. The reference flows for all 5 t-shirts.*

T-shirt style	Style number	Fibre composition	Reference flow
03	0300 	Virgin polyester-Better Cotton (poly-cotton)	1 t-shirt made of 60% of Better Cotton and 40% of virgin polyester
	0370 	Recycled polyester-Better Cotton (poly-cotton)	1 t-shirt made of 60% of Better Cotton and 40% of recycled polyester
05	0510 	100% Conventional cotton	1.816 t-shirts made of 100% cotton (conventional, organic or Better Cotton)
	0552 	100% Organic cotton	
	0552b	100% Better Cotton	

The t-shirts with the same fibre composition (considering cotton and polyester) have an identical estimated number of times of washing. For t-shirts style 03, this number is 200 times, while for t-shirts style 05, it is 110 times. In reality, the number of cycles that a t-shirt experiences before the end of its life as a t-shirt varies. The average numbers of washing were estimated together with the commissioner, considering a range of factors. Please see Table 7 for a more detailed explanation

LCI MODELLING FRAMEWORK AND HANDLING OF MULTIFUNCTIONAL PROCESSES

The study is made based on what was previously explained that changes in the studied system do not have large-scale effects on the background system (such as change of grid mix in a country). However, in reality, every change in even small systems accommodates changes in the larger, surrounding systems.

Multifunctional processes

Multifunctional processes are processes that serve two or more purposes. The choice of methodology also affects how multifunctional processes are handled. An example could be the generated waste fabric from a cutting process. This fabric is necessary for making the intended final products, but the cut-off fabric might serve another purpose. For instance, it could be used as an input material for a smaller textile product. Several ways, depending on the modelling choice, exist that help to divide the emission arising from the production of the fabric that mostly goes for producing the main product, and for the secondary product.

Since in the present project, consequential modelling is used, the way of handling this would be through system expansion. This means that the "part of the world" that the LCA takes into consideration expands to include this other product. The way this works is by asking the question "how would this secondary product have been produced if it was not for the production of the main product?". In other words, how would one produce small textile items if one did not have access to the cut-off fabric? The answer to this question then is what has been "saved".

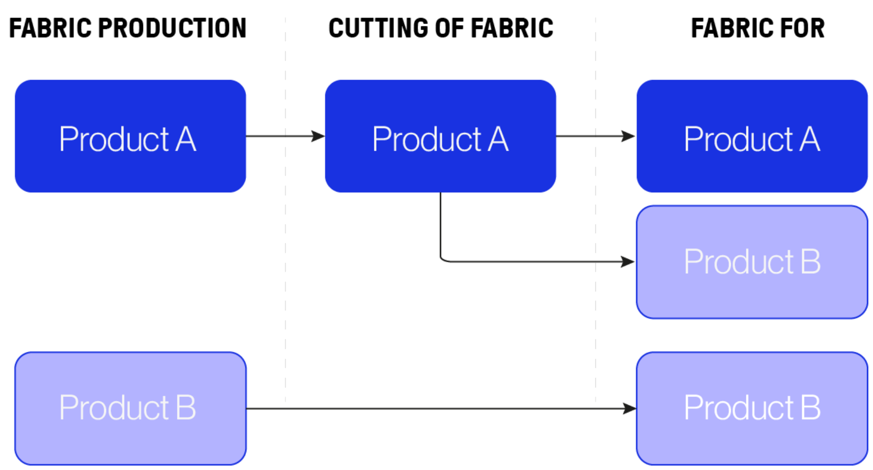

Figure 2*. An illustration of the system expansion*

Calculating the environmental impact of product B by itself would provide the “savings” that can be attributed to product A which is providing input material to product B.

This approach to consequential modelling strives to capture all the changes that the system has on the environment.

The attributional modelling, however, functions differently. Like consequential modelling, system expansion is the primary option. However, allocation can be made if system expansion is not feasible or easily accessed. This would preferably be conducted on a physical characteristic. In the example above, the production of the fabric until the cutting stage would be split in relation to the weight of the main fabric and the cut-off fabric. If 10% of the fabric is cut-off for use in the other product, then 10% of the environmental impact is discarded from the fabric for the main product.

In this case, weight is most sensible while in other scenarios, volume or other physical attributes could be more meaningful. If this is not possible or sensible, the next option would be to perform allocation according to another physical relationship. If this is not possible, then the ISO hierarchy states that it is possible to allocate according to another parameter, for instance, an economic parameter.

The secondary functions performed in this study will be described in the chapter concerning Life Cycle Inventory. For the primary modelling of the system, this study is using the consequential approach, which means that system expansion is always used when it is not possible to subdivide a process.

Both approaches (consequential and attributional) use the allocation hierarchy described in ISO 14044. In short, the hierarchy sets the order of ways of which to divide impacts between outputs when one single process results in more than one product.

SYSTEM BOUNDARY AND COMPLETENESS REQUIREMENTS

It is important to state which parts of the life cycle are being included to have a clear understanding of where the environmental burdens are arising from. The system boundary of this study includes the entire life cycle from cradle-to-grave. Figures 3 to 7 indicated the illustration of the system for each t-shirt.

The boundary is marked with a black dotted line, the blue dotted line marks the technosphere, the “surrounding economy”, and the green line represents the ecosphere which is “the environment”. Arrows show where resources and pollution shift from one sphere to another. The model also distinguishes the foreground system from the background systems, using the highlighted area (in this figure the pink area is the foreground system).

The foreground system consists of (1) processes that are specific to the studied product’s life cycle and (2) processes that the commissioner has close ties to. The foreground system will, therefore, be modelled using both primary data provided by ID® IDENTITY, and secondary data from databases and academic literature. Furthermore, from a management perspective, processes in the foreground system may be changed by the commissioner, who has the power to change or influence the processes, e.g., via purchase decisions. A change can occur by choosing another supplier or influencing the way a unit process is operated.

The model below shows all the processes required to fulfil the functional unit. The largest flow is seen at the top of the model and starts with the extraction of raw materials.

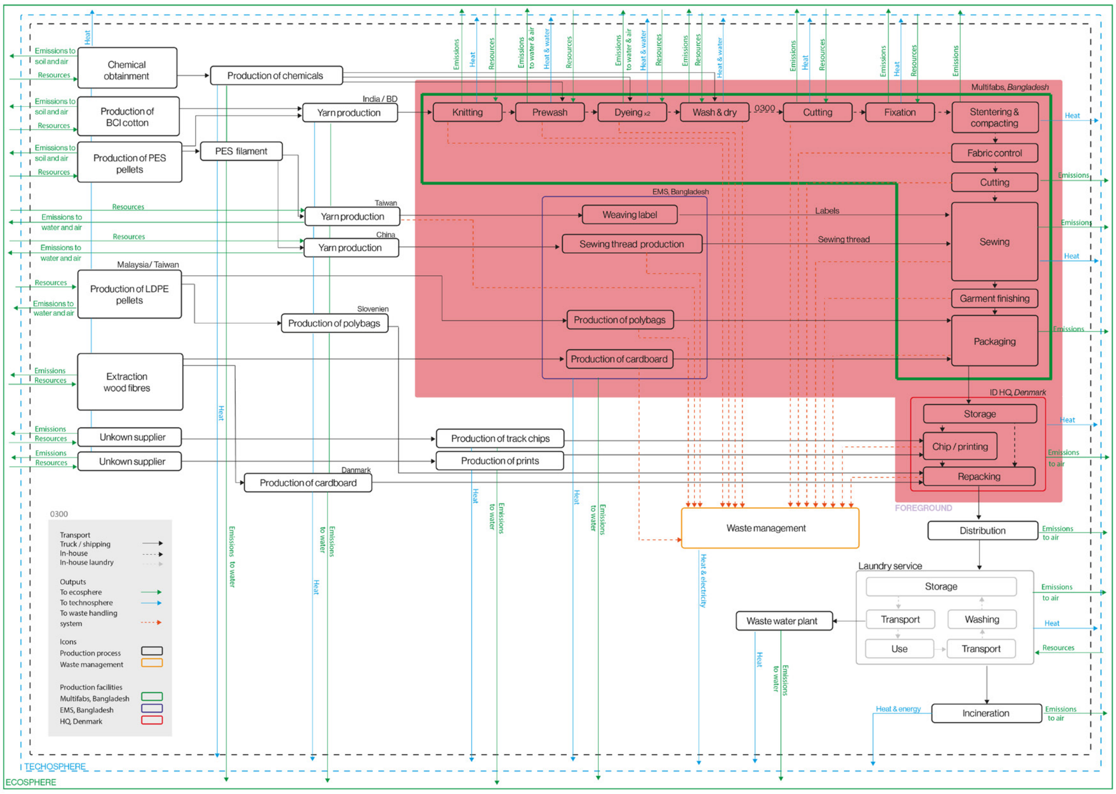

***Figure 3.** Flow chart of t-shirt 0300.*

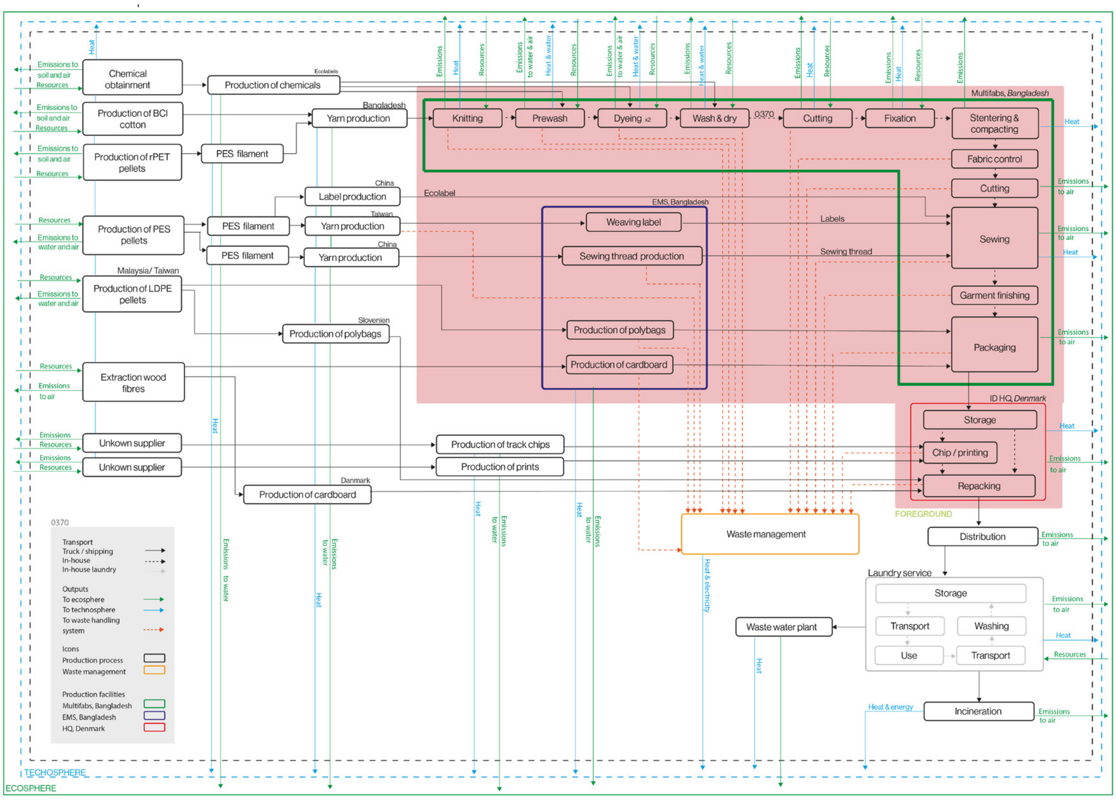

***Figure 4.** Flow chart of t-shirt 0370.*

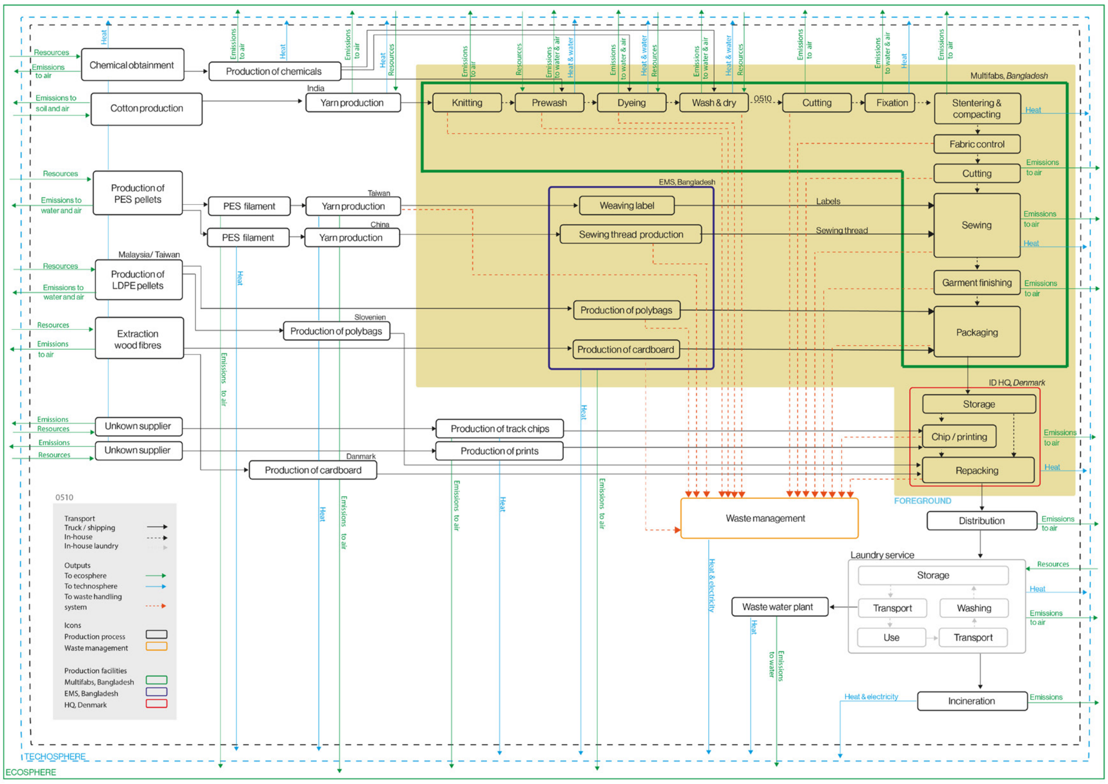

Figure 5. *Flow chart of t-shirt 0510.*

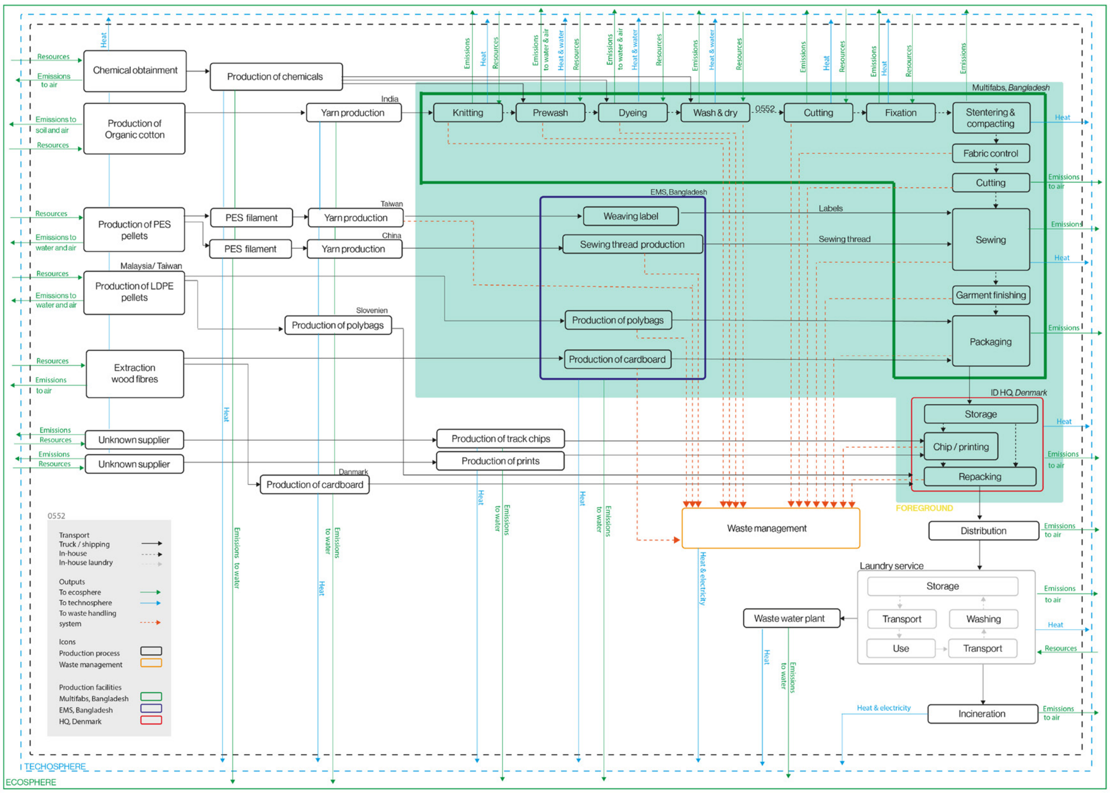

Figure 6. *Flow chart of t-shirt 0552.*

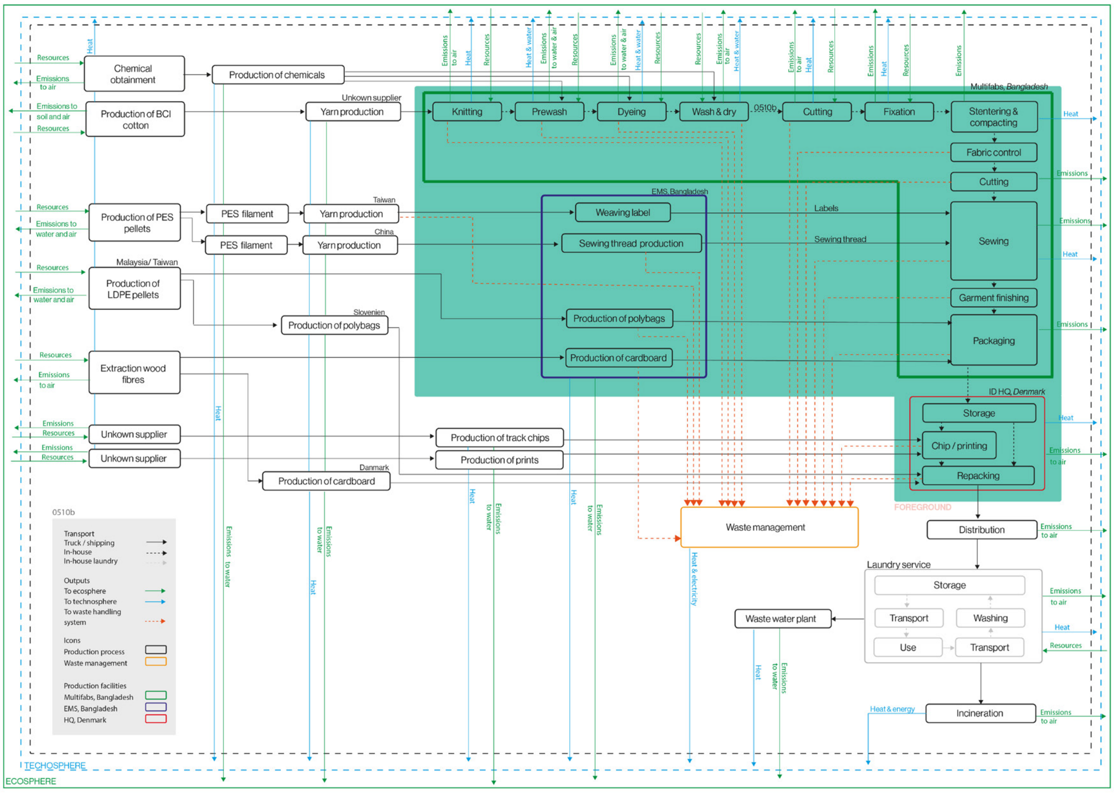

Figure 6. *Flow chart of t-shirt 0552b.*

As can be seen in Figure 3 to 7, the overall steps to produce the final products seem to be similar. However, depending on the primarily materials used, there are some differences between the t-shirts under the study:

- Comparing the flow chart of t-shirts style 03, the source for producing fibre for t-shirt 0370 is from recycled polyester, while for 0300, it is the extraction of crude oil from the ground.
  Also, t-shirt 0370, has an extra labelling production which indicates the eco-label labelling.
- T-shirts style 05, are coming from different farms with different approaches. For example, to produce organic cotton, no industrial chemicals are used (neither industrial fertiliser nor pesticides or herbicides). Also, Better Cotton, controls the use of chemicals, water and other steps that need to be taken to grow the cotton.

COMPLETENESS REQUIREMENTS

Regarding the completeness requirements, we exclude infrastructure, capital equipment, environmental burden related to most administrative processes, etc. Essentially, this means that the study slightly underestimates the environmental impact of the t-shirts since such processes are required to create the products. As we are not doing hybrid LCI e.g., Exiobase background modelling (Exiobase Consortium 2015) based on unit process and not from input & output statistics, this underestimation is tiny since the environmental impacts should be divided between multiple products, and in the case of infrastructure and capital equipment, over many years as well.

More in detail, the construction of capital goods such as sewing machines used in the Cut-Make-Trim phase is not considered. However, the machines used to create different t-shirts are the same, and the number of minutes needed to sew pieces together is similar (6 minutes for 0370, 5 minutes and 40 seconds for 0300, 4 minutes and 46 seconds, and 5 minutes and 42 seconds for 552/552b). Thus, this will not have any significant impact on the analysis. A rough calculation can show this. Say that it takes 5 minutes to sew a product and during a workday of 7 hours (excluding breaks), the sewing machine is running 80% of the time. This is true 5 days a week for 50 weeks per year. The sewing machine lasts 10 years before it needs replacement. Therefore, among a total of 1,092,000 minutes of the machines' total run-time, the product should be allocated 5 of those minutes. Hence, 0.000045% of the allocated environmental impact of the sewing machine, should be attributed to the t-shirt.

The environmental burden of the sewing machine is, therefore, very small and will not be considered in this study. However, it is important to mention that the energy required for running the sewing machine is taken into account. The rule applied also to storage facilities, etc.

Moreover, there are some processes that is not included in the ecoinvent database. One of these is oil production from cotton seed and as a substitute it considers palm oil. This underestimates the impact of the result for cotton with approximately 1250 CO2 eq. (Weidema, 2023, personal communication, February 2do) However, LCAs take different approaches and since all databases and methodologies have their strengths and weaknesses it is important to understand them. Note that the results of this study are valid based on the modelling and calculating these missing data in the database are not included as part of the scope

REPRESENTATIVENESS OF LCI DATA

The aim of this study (or any LCA study for that matter) is to model reality as accurately as possible. In this part we will evaluate the representativeness of our data based on three parameters: Geographical, Temporal and Technological.

Geographical

The production of the t-shirts primarily takes place in Bangladesh, while many of the materials come from other places which not all of them are known. The products are made with a special focus on the European market. During the production, the electricity mix will be country or region specific. For this study, we will model the situation of the t-shirts being distributed from Denmark, and sold, used, and incinerated in Denmark and the nearby European countries such as Germany. The use of the t-shirts affects the amount of energy consumption and this because the energy produced for washing the clothes is generated from different sources in different countries (some generate energy more fossil-based than the others). As well, the country in which a product life ends is relevant to decide if the product incineration or landfills. It can be concluded that the overall geographical data in the foreground system has a high representativeness.

Temporal

Even though we can see progress on the innovative front in the textile industry, the representativeness of the study is high on this parameter. It is not assumed that any processes will change over the course of lifetime of the functional unit. As an example, waste handling and the production of cotton is likely to remain the same for a long period of time, even though we can see that recycling technologies are being developed and new EU legislation emerging.

Technological

It is important that the data on technological components is representative. This is due to its impact on the consumption of resources such as water and energy. For instance, data about the machinery used during Cut-Make-Trim should be known to determine the consumption of energy.

In Table 4, an overview of the data specificity and dimension of the 5 t-shirts is provided.

***Table 4**. An overview of the specifcity and dimensions of the data collected for each process of the production of the t-shirts.*

Processes	T-shirt style					Specificity ** (Table 5)	Data dimension	
	0300	0370	0510	0552b	0552b			
Production phases							Source	Access
Main materials	Better Cotton & Polyester	Better Cotton & Recycled Polyester	Conven-tional Cotton	Organic cotton	Better Cotton	Very high	Compliance Specialist at ID® IDENTITY	Excel inventory table document
Spinning & weaving	Bangla-desh	Bangla-desh	Bangla-desh	Bangla-desh	Bangla-desh	Very high	Compliance Specialist at ID® IDENTITY	Excel inventory table document
Use	Denmark & other European countries	Denmark & other European countries	Denmark & other European countries	Denmark & other European countries	Denmark & other European countries	Low to very low	Use pattern: LCA specialist at Tekstil-revolutionen together with commissioner Laundry sys-tem: Ecoin-vent database and desktop research"	Ecoinvent database and research
Incineration	Denmark	Denmark	Denmark	Denmark	Denmark	Low	LCA specialist at Tekstilrevo-lutionen	EcoInvent-database

***Table 5.** Data specifcity explanation (Hauschild et al. 2018)*

Data specificity	Explanation
Very high	When the data is directly measured from a specific site
High	When the data is derived from a result of measurement at a specific site via modelling
Medium	When the data is provided using LCI database process or literature related to the actual process
Low	When the data is provided using generic LCI database process or literature
Very low	When the data is provided by the judgement of a relevant expert or as the last option an LCA practitioner.

PREPARATION OF THE BASIS FOR THE IMPACT ASSESSMENT

The selection of the impact categories coverage is based on the Goal and Scope definition of the LCA. The goal is to unveil the environmental and climate impacts of the 5 t-shirts. These categories which need to be examined are primarily the impact of the chemical release to wastewater, particle pollution to air, and consumption of water. Furthermore, greenhouse gases are emitted indirectly through the consumption of energy that comes from burning fossil fuels, and directly from the pollution during the transportation of the products. An extensive list of impact categories is in Table 6 and for further explanation of each category please see Appendix C.

Table 6.: *The 22 impact categories at the midpoint, endpoint level, as well as Water Scarcity that this study will evaluate the products based on.*

Impact Category	Abbreviation	Unit
Midpoint level		
Global Warming Potential	GWP	kg CO_2 eq
Stratospheric Ozone Depletion	SOD	kg CFC-11 eq
Ionising Radiation	IR	kBq Co-60 eq
Ozone Formation, Human Health	OF,HH	kg NOx eq
Fine Particulate Matter Formation	FPMF	kg PM2.5 eq
Ozone Formation, Terrestrial Ecosystems	OF,TE	kg NOx eq
Terrestrial Acidification	TA	kg SO_2 eq
Freshwater Eutrophication	FWE	kg P eq
Marine Eutrophication	ME	kg N eq
Terrestrial Ecotoxicity	TET	kg 1,4-DCB
Freshwater Ecotoxicity	FWET	kg 1,4-DCB
Marine Ecotoxicity	MET	kg 1,4-DCB
Human Carcinogenic Toxicity	HCT	kg 1,4-DCB
Human Non-carcinogenic Toxicity	HNCT	kg 1,4-DCB
Land Use	LU	m^2a crop eq
Mineral Resource Scarcity	MRS	kg Cu eq
Fossil Resource Scarcity	FRS	kg oil eq
Water Consumption	WC	m^3
Water scarcity		
Water Scarcity	WS	m^3 world eq/m3
Endpoint level		
Human Health	-	DAILY
Ecosystem	-	species.yr
Resources	-	USD2013

The assessment will be carried out in the LCA software SimaPro with the data being analysed based on the ReCiPe 2016 LCIA method and the generic data is sourced from ecoinvent.

The ISO 14040/14044 standards distinguish between mandatory and optional steps in the LCIA phase, where characterisation (linking the processes of the system to impact categories) is mandatory, normalisation (comparing these impacts to a fix-point, such as the environmental impact of one year of an average person's life) and weighting (ascribing differentiated importance to the impact categories) are not. However, this study will provide all of three in an attempt to make the results and conclusions more usable and relevant for the commissioner.

PLANNING THE REPORTING OF RESULTS

Conclusions, results and the reporting are intended for both internal use of the commissioner, as well as public disclosure.

TEKSTIL REVOLUTIONEN

LIFE CYCLE INVENTORY

The Life Cycle Inventory section will elaborate on the approach to collecting data and how the system has been modelled.

The Life Cycle Inventory section will elaborate on the approach to collecting data and how the system has been modelled. In addition, a reflection on data collection will be provided. For an overview of the full list of assumptions please refer to Appendix D. collecting data and how the system has been modelled. In addition, a reflection on data collection will be provided. For an overview of the full list of assumptions please refer to Appendix D.

DATA COLLECTION

The source for collecting data depends on the availability of data. The data for the foreground system of 5 t-shirts is primarily provided by the commissioner, while the background system is modelled by the data provided from the ecoinvent database 3.9 in SimaPro software (3.6 as to consequential-unit processes), academic literature and other databases. Metadata based on dimension and data specificity as shown in Table 4 and Table 5, respectively are included to provide an overview of the accuracy of the collected data for each stage of the product's life cycle.

SYSTEM MODELLING PER LIFE CYCLE STAGE

This section will cover the processes that are chosen based on actual data provided by ID® IDENTITY or main assumptions, and the gaps between the data. A list of assumptions in more detail per life cycle stage can be found in Appendix D.

Raw material stage

The t-shirts produced by ID® IDENTITY are made of a combination of cotton and polyester in the case of t-shirts 0300 and 0370, and 100% cotton for 0510, 0552 and 0552b. However, the types of cotton produced for the latter three t-shirts are different from each other. 0510's material is 100% conventional cotton, while 0552 is made of 100% organic cotton. 0552b, as it is a possible future scenario, is imagined to be made of Better Cotton.

The processes for these t-shirts are chosen from the database and modified using the data collected by ID® IDENTITY. Also, some of the textile materials have been modelled from raw materials or via similar processes. Data for some products such as detergents, softeners and dyestuff are not exactly available in the database. Therefore, they have been created based on Mistra Future Fashion (Sandin et al. 2019)'s study of life cycles on Swedish garments. This information has been combined with the data collected by ID® IDENTITY.

The extraction of raw materials such as petroleum are assumed to be based on the standard machinery. The product system consists of multifunctional processes, which means that the process of producing the final product has more than one final output. These secondary products and their environmental performances are not directly ascribed to the t-shirt in this study. They need to be treated differently. To handle the multifunctional process, this report is following the ISO 14044 Hierarchy.

Virgin polyester

The process for producing polyester - from the extraction of the raw material to production - is modelled based on generic data that are chosen from the ecoinvent database. T-shirt 0300 includes 40% virgin polyester and the rest is made of cotton.

Recycled polyester

The process for producing polyester - raw material to production - is modelled based on generic data that are chosen from the ecoinvent database. 40% of this recycled polyester is used in t-shirt 0370 and the rest is made of cotton.

Conventional cotton & Organic cotton

The production of both conventional and organic cotton is modelled based on the processes available in the ecoinvent database. However, the organic process is adjusted by adding the same irrigation subprocess and amount. This is because the organic cotton process did not include irrigation. T-shirt 0510 is made of 100% conventional cotton and the t-shirt 0552 is made of 100% organic cotton.

Better Cotton

Better Cotton is conventional cotton embedded in the Better Cotton Initiative. This initiative provides training to primarily small-scale farmers to optimise production, for example by education on the use of pesticides and fertiliser as well as water management (Better Cotton, no date). Although Better Cotton accounts for between 20% and 30% of all cotton produced globally, there is no available data on this type of cotton in the databases.

Since there were no available Better Cotton processes in the databases, the Better Cotton process has been constructed using the conventional cotton process in ecoinvent as a base and modified based on Life Cycle Assessment of Organic, Better Cotton and Conventional Cotton: A Comparative Study of Cotton Cultivation Practices in India (Shah, P., Bansal, A., Singh, R.K. , 2018). This study compares organic, conventional and Better Cotton farms according to different parameters such as water consumption, urea & pesticide use, yield and seed amount. For a deeper dive into the calculations, see Appendix F.

The Better Cotton is used in t-shirt 0552b (100%), t-shirt 0300 (60%) and t-shirt 0370 (60%).

Manufacturing stage

Manufacturing process includes Yarn production, Fabric production, Dyeing process and Cut-make-trim.

Electricity
In yarn production, the consumed electricity is based on generic data obtained from the report (Sandin, et al., 2019). The data on electricity for Fabric production and dyeing processes instead are based on the measured data given by ID® IDENTITY. Therefore, the quality of the latter data is high and reliable, meaning that it has a very high specificity. This is true for all of the 5 t-shirts.

Transportation
The overall accuracy of the transportation from cradle-to-grave of this report has a medium specificity.

Data on transportation from the fibre extraction and production is based on generic data obtained from the database in SimaPro. However, the data from fibre production to the distribution is given by ID® IDENTITY.

Cut-Make-Trim
Cut-Make-Trim is where the products get sewn together. It is the stage where collection of many components happens. This stage has a high specificity since all the data is given by the company.

Yarn production

Yarn produced in t-shirts 0300 & 0370 is a combination of polyester and cotton, whilst t-shirts 510, 552 and 552b are single-yarns made of cotton only.

Fabric production

The fabric used for all t-shirts is made with knitting technique. No water or chemicals were used to produce the fabric. Data on fabric production is provided by the company and therefore, it has a high certainty.

Dyeing process

The dyeing process includes dyed fabric which contains prewash, dyeing and wash & dry process. Each of the mentioned processes requires a specific water amount, electricity and chemical. Chemicals used for dyeing the fabric differ in t-shirt 0370 compared to the other 4 t-shirts. The list of chemicals for all t-shirts can be found in Appendix A and B. Specific chemical composition is not available due to commercial interest. T-shirts 0300 and 0370 are going through two dyeing processes (2 dye baths), but the t-shirts style 05 are dyed through one dyebath.
Among all the t-shirts, only style 0370 is approved for eco-labelled textiles.

Use stage

This stage includes Distribution & Repacking and the washing process.

Distribution & Repackaging

Two types of packaging - polybags and cardboard boxes - are used to transport the t-shirts from production facilities in Bangladesh to the distribution centre in Denmark, and also from the headquarter in Denmark to the end-users. The data on the production of packaging both in Denmark and Bangladesh are modelled based on generic data obtained from the database. The repackaging process in Denmark is done by machine. The consumed electricity is the same electricity as the storage used to repack the t-shirts. The data on Packagings such as the weight of the packages and the number of t-shirts in them are provided by the company.

- The number of t-shirts in polybags in Denmark is assumed to be 1 and 15 in Bangladesh
- The number of t-shirts in cardboard boxes in Denmark is 9.08 and in Bangladesh is 50.

Washing

The specificity of the data on the use stage (washing) is low to very low. This is because the information available on the number of washing for each t-shirt varies significantly (between 75-150 washes, with an average of 110 washes for the cotton t-shirts (accounting to a variation of -32% to +36%) and between 150 and 250, with an average of 200 washes for the poly-cotton t-shirts (accounting for a variation of -25% to +25%) based on estimates from the commissioner). Moreover, the amount of water being used and the types of chemicals such as detergents used to clean the t-shirts are taken from the Mistra Future Fashion report (Sandin, et al., 2019).
Therefore, to model the washing, the processes are chosen from the generic data available in the database and adjusted based on studies found in the literature. The number of washes is based on the fibre composition as can be seen in the Table 7 below.

The temperature recommended for washing the t-shirts is 60 degrees (except for the t-shirt 552b, since it is a non-existing scenario, the data on how to take care of it is not provided - in which case the same temperature has been assumed).

The processes for chemicals, the amount of detergent and electricity use for washing has been found in the literature (Sandin, et al., (2019)). The number of washes in the Product Environmental Footprint Criteria Rules Version 1 for all types of t-shirts made of different materials such as polyester, cotton, viscose, polyamid, etc., is assumed to be 52 times as a standard number (Quantis, 2021), although version 1 was outdated in 2019, it is still recent and the number considerably lower compared to the minimum number of washes for t-shirts in this study.

Table 7. *The average times of washing, provided by* ID® IDENTITY.

Fibre composition	Private - times of washing	Industrial - times of washing
40%Poly-60%Cotton (0300 & 0370)	150 - 250	150 - 250
100% Cotton (0510, 0552, 0552b)	75 - 150	75 - 150
Average	110 times for t-shirts style 05 and 200 times for t-shirts style 03	

Regarding private use, based on ID® IDENTITY's recommendation, the t-shirts style 05, which are made of 100% cotton, have a minimum of 75 and a maximum of 150 times washing. This number of times is based on regular washing for private use. However, it is important to take different variables for the lifespan of the garments into consideration.

These variables are potentially how customers take care of the t-shirts in terms of using and cleaning t-shirts, as well as when the t-shirts are worn out.

ID® IDENTITY has limited influence on how the customer washes the garment in terms of the type of detergent they use and the temperature. Also, the purpose of using the t-shirts can vary from light daily activity to office use to the work environment where t-shirts are exposed to environmental stresses such as carpentry.
On the other hand, t-shirts style 03 that are made of 60% cotton and 40% polyester fibre compounds are specially made to last longer during the industrial wash of the garments. Still, the quality of the clothes when washed in industrial washing is dependent on how the industry treats the garment during the washing and drying process. Wrong use of chemicals such as the extra use of bleaching and disinfectants has been reported in the industry, especially during the covid-19 pandemic. Another reason that could affect the lifespan of garments is accidents during the washing process. This could happen, for example, when washing the garment with neglected sharp objects.

Moreover, what is considered worn out, presentable or 'as new' varies from customer to customer which makes it difficult to judge and quantify. Together with ID® IDENTITY it was decided, based on durability tests, general knowledge of the products and customer feedback that the minimum number of washes for the polycotton t-shirts were 150 washes while the maximum were 250 times. For the 100% cotton t-shirts, the minimum was set to 75 and the maximum to 150.

The explanation above could eventually be relevant to all t-shirts both in the industrial and private wash. Hence, communication with end users, no matter private or industrial, plays an important role in prolonging the t-shirts' lifespan, in which ID® IDENTITY tries their best to create awareness among their customers and inform them about the washing procedures of their t-shirts. It is important to remember that there are differences between private and professional wear, when it comes to for example construction, fashion-trends and logistics. Thus, caution should be taken if wanting to use these conclusions, results or assumptions for estimating the environmental performance of clothes for private use.

The minimum and the maximum number of washing for t-shirts with different fibre compositions are assumed to be the same, when cleaning them in private and industry wash. This is because the numbers of washing could not be separated. More in detail, an industrial washing environment could be harsh on a garment. However, well-informed industrial washing could also expand the lifetime of garments. Besides, in both industrial and private wash, it is possible to achieve results that are better or worse than expected. The possible variations in private washing and industrial washing set the two options equal. Both may have a noticeable positive or negative environmental impact on the garment depending on conditions that are out of the company's control.

Disposal stage (end-of-life)

Since ID® IDENTITY does not recycle or reuse the t-shirt after its lifespan is over, it is assumed that the t-shirt waste is treated via incineration. There is no data available on the distance from the incineration plant, energy use & production and gas emissions, therefore, the data is modelled using the generic process from SimaPro's database. This means that the specificity of the data is low. The end-of-life scenario has been modelled based on Sandin, *et al*. (2019).

CALCULATED LCI RESULTS

After creating a model of a system, it is possible to calculate the results by assigning all the processes in the model to one or more impact categories. With all processes having the assigned environmental impacts, these are summed to show the impacts of the whole (or part of the) model. This means that for each impact category, there is a result stating a value. This is shown in Figure 9 below. For more in-depth information on the different impact categories and what they stand for, see Appendix C.

Hotspot and sensitivity analysis result and calculation detail could be found in Appendix E.

Regarding the calculation of the distance from the distribution to the laundries, an estimating calculation is done that could be found in Appendix H.
The list of the inventory table including the data from raw material extraction to the waste treatment is provided by ID® IDENTITY and this LCI could be accessed in Appendix I.

The Chemical Oxygen Demand (COD) level in the wastewater process in the SimaPro database is adjusted based on the COD level recorded by the company for one year in 2021. This information is collected in Appendix J.

Appendix X1 to X4 are the t-shirt's measurement charts which is the detailed indication of the t-shirt size and the fit. Having in mind the measurement chart for t-shirt -552b do not exist as a physical document as it is an imaginary scenario; however, as it is similar to the 0552, the same measurement is considered for 0552b, too.

Colours in Tables 8-11 and 13-17, indicate the level of the environmental performance that each t-shirt has in each impact category. The colours indicate the highest impact to the lowest by going from red to green, respectively (Figure 8).

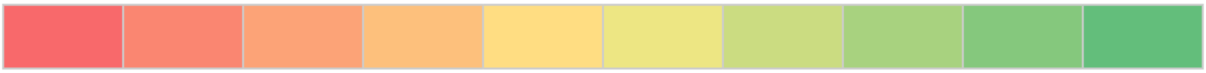

Figure 8. *Colour code indicator for the environmental impact assessment*

Tables 8-11 and 13 should be read horizontally since each impact category has a different unit. However, Tables 14-17 could be vertically read as they share the same unit.

TEKSTIL REVOLUTIONEN

LIFE CYCLE IMPACT ASSESSMENT

The Life Cycle Impact assessment section of the report will present the calculated impacts of life cycles of 5 t-shirts.

CHARACTERISED RESULT

Characterised results are calculated in Tables 8-11, and the results for the characterisation of the midpoint can be found in Table 8. These categories can be made into endpoint categories if a simplification is needed (see Table 11). The endpoint category is an indication of long-term damage that affects the midpoint categories. The midpoint characterisation normally consists of 16-18 categories, the endpoint consists of just three; Natural Environment, Human Health and Natural resources.

Below one will find an illustration of the relationship between the midpoint and the endpoint categories.

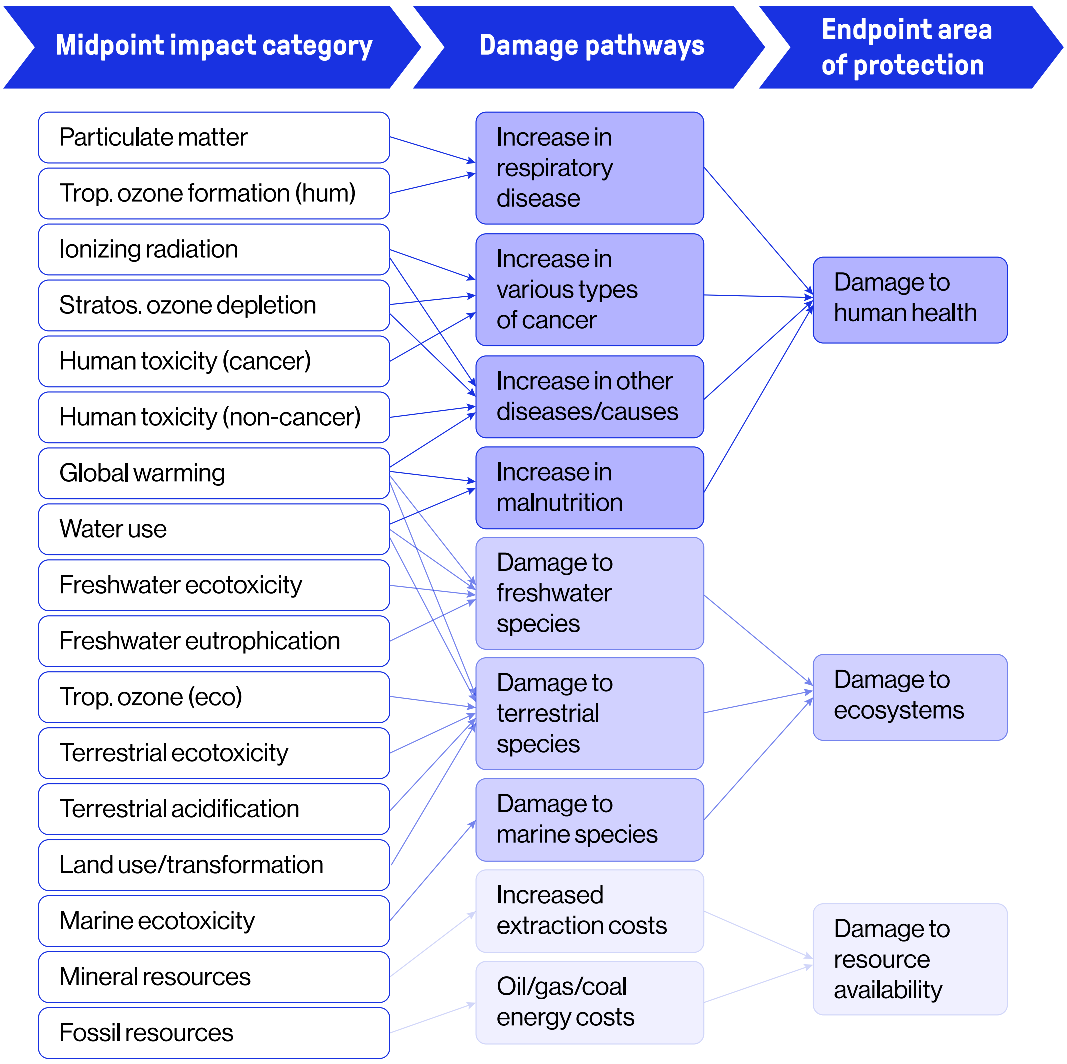

Figure 9. *The overview of the ReCiPe structure indicating the midpoint and endpoint levels (SimaPro 4.15, 2020)*

Ecosystem is expressing the fraction of species in an ecosystem that potentially disappears in an area during a certain time period as a result of the environmental impact. The category is measured in the unit $species * year$ (*SimaPro 4.15, 2020*).

Human health is a concept expressing the number of human life years potentially lost as a result of the environmental impacts. It considers the severity of diseases in terms of disability and death and how much the environmental impacts are attributed to these diseases. The measurement is DALYs (Disability Adjusted Life Years) and is used by WHO (2020) among others. The unit is $year$ (*SimaPro 4.15, 2020*).

Resource scarcity refers to the additional costs of producing natural resources in the future, assuming that annual production rates stay constant over an infinite period of time. These costs are measured using a 3% discount rate. The unit for this measurement is $USD2013$ (*SimaPro 4.15, 2020*).

Midpoint values

***Table 8**. Characterised result of the 5 t-shirts, at midpoint level for 18 impact categories with the consequential approach. Values must be read horizontally since the units of each category are different.*

		Virgin polyester -Better Cotton	Recycled polyester -Better Cotton	Conven-tional cotton	Organic cotton	Better Cotton
Impact category	**Unit**	**T-shirt 0300**	**T-shirt 0370**	**T-shirt 0510**	**T-shirt 0552**	**T-shirt 0552b**
Global Warming Potential	kg CO_2 eq	8.29E+00	7.23E+00	9.80E+00	5.85E+00	9.65E+00
Stratospheric Ozone Depletion	kg CFC11 eq	6.93E-05	6.24E-05	1.25E-04	3.80E-05	1.24E-04
Ionizing Radiation	kBq Co-60 eq	3.07E-02	2.91E-02	2.89E-02	2.62E-02	2.85E-02
Ozone Formation, Human Health	kg NOx eq	7.91E-02	7.72E-02	6.68E-02	6.35E-02	6.63E-02
Fine Particulate Matter Formation	kg PM2.5 eq	2.75E-02	2.56E-02	3.12E-02	2.22E-02	3.07E-02
Ozone Formation, Terrestrial Ecosystems	kg NOx eq	7.96E-02	7.77E-02	6.72E-02	6.39E-02	6.67E-02
Terrestrial Acidification	kg SO2 eq	8.76E-02	8.46E-02	1.07E-01	6.58E-02	1.05E-01
Freshwater Eutrophication	kg P eq	5.86E-02	5.85E-02	1.42E-01	9.37E-03	1.42E-01
Marine Eutrophication	kg N eq	9.51E-02	9.50E-02	2.28E-01	1.99E-02	2.28E-01
Terrestrial Ecotoxicity	kg 1,4-DCB	9.28E+01	9.10E+01	7.72E+01	7.20E+01	7.69E+01
Freshwater Ecotoxicity	kg 1,4-DCB	4.43E-01	3.91E-01	1.03E+00	8.07E-02	1.02E+00
Marine Ecotoxicity	kg 1,4-DCB	5.91E-01	5.51E-01	1.32E+00	1.37E-01	1.31E+00
Human Carcinogenic Toxicity	kg 1,4-DCB	4.11E-02	4.53E-02	2.58E-02	4.59E-02	2.48E-02
Human Non-carcinogenic Toxicity	kg 1,4-DCB	-1.95E+01	-1.98E+01	-7.18E+01	1.10E+01	-7.18E+01
Land Use	m^2a crop eq	3.63E+01	3.63E+01	3.10E+01	3.73E+01	3.10E+01
Mineral Resource Scarcity	kg Cu eq	6.52E-02	4.44E-02	1.40E-01	3.53E-02	1.34E-01
Fossil Resource Scarcity	kg oil eq	2.42E+00	2.13E+00	2.45E+00	1.91E+00	2.41E+00
Water Consumption	m^3	6.66E-01	6.47E-01	8.68E-01	8.16E-01	7.44E-01

Table 8 indicates the actual environmental burden of each t-shirt on different impact categories. It can be seen that the contribution of t-shirt 0510 on the environment is more noticeable compared to the other t-shirts, especially on 11 out of 18 impact categories. However, the burden of this t-shirt is lower on 3 impact categories; namely, Human carcinogenic toxicity (kg 1,4-DCB), Human non-carcinogenic toxicity (kg 1,4-DCB), and Land use (m^2a crop eq).

In contrast, t-shirt 0552 shows the least environmental burden on most of the impact categories.

Comparing environmental damage of the 3 t-shirts made of cotton the results could be shown as t-shirt 0510 > t-shirt 0552b > t-shirt 0552; where > indicates higher environmental burden. Also, taking a look at the t-shirts with mixed fibres, the environmental impact of t-shirt 0300 is bigger than the impact of t-shirt 0370. When a stage or even a unit process in an life cycle dominates the overall results of an impact category, this contribution can be excluded to better show the environmental impact of other stages or unit processes. The results after excluding this process are shown in Table 9.

***Table 9**. Characterised result of the 5 t-shirts, at midpoint level for 18 impact categories, excluding the seed-cotton production process. Values must be read horizontally since the units of each category are different.*

		Virgin polyester -Better Cotton	Recycled polyester -Better Cotton	Conven-tional cotton	Organic cotton	Better Cotton
Impact category	**Unit**	**T-shirt 0300**	**T-shirt 0370**	**T-shirt 0510**	**T-shirt 0552**	**T-shirt 0552b**
Global Warming Potential	kg CO_2 eq	6.28E+00	5.38E+00	4.73E+00	4.85E+00	4.73E+00
Stratospheric Ozone Depletion	kg CFC11 eq	2.22E-05	1.76E-05	8.78E-06	1.08E-05	8.78E-06
Ionizing Radiation	kBq Co-60 eq	2.97E-02	2.82E-02	2.62E-02	2.59E-02	2.61E-02
Ozone Formation, Human Health	kg NOx eq	7.62E-02	7.45E-02	5.93E-02	5.94E-02	5.93E-02
Fine Particulate Matter Formation	kg PM2.5 eq	2.35E-02	2.18E-02	2.08E-02	2.07E-02	2.09E-02
Ozone Formation, Terrestrial Ecosystems	kg NOx eq	7.67E-02	7.51E-02	5.97E-02	5.98E-02	5.97E-02
Terrestrial Acidification	kg SO_2 eq	6.61E-02	6.37E-02	5.30E-02	5.30E-02	5.30E-02
Freshwater Eutrophication	kg P eq	6.58E-04	5.94E-04	1.65E-04	2.35E-04	1.67E-04
Marine Eutrophication	kg N eq	2.76E-03	2.70E-03	2.20E-03	2.21E-03	2.20E-03
Terrestrial Ecotoxicity	kg 1,4-DCB	8.97E+01	8.82E+01	6.92E+01	6.94E+01	6.92E+01
Freshwater Ecotoxicity	kg 1,4-DCB	3.43E-02	3.26E-02	2.35E-02	2.50E-02	2.35E-02
Marine Ecotoxicity	kg 1,4-DCB	7.67E-02	7.36E-02	5.95E-02	6.02E-02	5.95E-02
Human Carcinogenic Toxicity	kg 1,4-DCB	4.98E-02	3.97E-02	4.62E-02	4.61E-02	4.61E-02
Human Non-carcinogenic Toxicity	kg 1,4-DCB	1.45E+01	1.43E+01	1.12E+01	1.12E+01	1.12E+01
Land Use	m^2a crop eq	3.46E+01	3.46E+01	2.69E+01	2.68E+01	2.69E+01
Mineral Resource Scarcity	kg Cu eq	2.32E-02	4.70E-03	3.14E-02	3.16E-02	3.14E-02
Fossil Resource Scarcity	kg oil eq	2.18E+00	1.93E+00	1.82E+00	1.81E+00	1.82E+00
Water Consumption	m^3	5.72E-01	5.53E-01	5.14E-01	5.10E-01	5.14E-01

Table 10 indicates the actual environmental performance of each t-shirt on different impact categories in the attributional modelling.

Table 10. *Characterised result of the 5 t-shirts, at midpoint level for 18 impact categories with an attributional approach. Values must be read horizontally since the units of each category are different.*

		Virgin polyester -Better Cotton	Recycled polyester -Better Cotton	Conven-tional cotton	Organic cotton	Better Cotton
Impact category	**Unit**	**T-shirt 0300**	**T-shirt 0370**	**T-shirt 0510**	**T-shirt 0552**	**T-shirt 0552b**
Global Warming Potential	kg CO_2 eq	9.21E+00	8.22E+00	1.17E+01	7.25E+00	1.15E+01
Stratospheric Ozone Depletion	kg CFC11 eq	7.88E-05	7.43E-05	1.48E-04	4.33E-05	1.47E-04
Ionizing Radiation	kBq Co-60 eq	3.63E-02	3.30E-02	3.63E-02	2.81E-02	3.52E-02
Ozone Formation, Human Health	kg NOx eq	8.11E-02	7.92E-02	7.08E-02	6.59E-02	7.04E-02
Fine Particulate Matter Formation	kg PM2.5 eq	2.57E-02	2.39E-02	2.83E-02	2.06E-02	2.78E-02
Ozone Formation, Terrestrial Ecosystems	kg NOx eq	8.17E-02	7.98E-02	7.13E-02	6.63E-02	7.08E-02
Terrestrial Acidification	kg SO_2 eq	8.95E-02	8.67E-02	1.10E-01	6.93E-02	1.09E-01
Freshwater Eutrophication	kg P eq	5.86E-02	5.86E-02	1.42E-01	8.12E-03	1.42E-01
Marine Eutrophication	kg N eq	9.44E-02	9.44E-02	2.26E-01	1.69E-02	2.26E-01
Terrestrial Ecotoxicity	kg 1,4-DCB	9.52E+01	9.36E+01	8.25E+01	7.43E+01	8.23E+01
Freshwater Ecotoxicity	kg 1,4-DCB	4.30E-01	4.28E-01	9.93E-01	8.32E-02	9.90E-01
Marine Ecotoxicity	kg 1,4-DCB	5.89E-01	5.86E-01	1.31E+00	1.29E-01	1.31E+00
Human Carcinogenic Toxicity	kg 1,4-DCB	4.26E-02	3.19E-02	2.72E-02	4.79E-02	2.62E-02
Human Non-carcinogenic Toxicity	kg 1,4-DCB	-1.96E+01	-1.98E+01	-7.19E+01	1.16E+01	-7.20E+01
Land Use	m^2a crop eq	8.85E+01	8.84E+01	1.58E+02	7.71E+02	1.58E+02
Mineral Resource Scarcity	kg Cu eq	5.92E-02	4.06E-02	1.25E-01	3.56E-02	1.19E-01
Fossil Resource Scarcity	kg oil eq	2.55E+00	2.29E+00	2.68E+00	2.14E+00	2.63E+00
Water Consumption	m^3	6.15E-01	5.96E-01	7.38E-01	8.05E-01	6.16E-01

Comparing the environmental performance results on impact categories in attributional modelling to consequential ones, the former also suggests the same results as the consequential modelling; meaning that among pure cotton t-shirts, the one with organic cotton has lower environmental burden, and between t-shirts 0300 and 0370, the latter has lower environmental impact.

However, considering some impact categories' results, it is important to take into consideration that this model is not made by all attributional processes; but only the processes that had the highest environmental impact on the process. This was done to provide a quick comparison when looking at the result focusing on the global environmental performance versus only the system attributed to the product.

Endpoint values

The endpoint (shown in Table 11) values indicate that conventional cotton (0510) and Better Cotton (0552b) have a higher total environmental impact on the Ecosystems and Resources damage categories. This is while, the organic (0552) cotton t-shirt has the highest impact on Human Health, compared to t-shirts 0510 and 0552b.

Table 11. *Characterised result of the 5 t-shirts, at endpoint level for 3 impact categories.Values must be read horizontally since the units of each category are different.*

		Virgin polyester -Better Cotton	Recycled polyester -Better Cotton	Conventional cotton	Organic cotton	Better Cotton
Damage category	**Unit**	**T-shirt 0300**	**T-shirt 0370**	**T-shirt 0510**	**T-shirt 0552**	**T-shirt 0552b**
Human Health	DALY	2.20E-05	1.97E-05	1.42E-05	2.37E-05	1.35E-05
Ecosystems	species.yr	4.22E-07	4.17E-07	4.40E-07	3.86E-07	4.38E-07
Resources	USD2013	9.29E-01	8.39E-01	8.99E-01	6.99E-01	8.84E-01

T-shirts 0300 and 0370 are also environmentally impactful on all the damage categories, within the same range.

As the Ecosystem impact category indicates the damage on the species annually, this category is also used to estimate the damage on biodiversity. Organic cotton (0552) among all of the 5 t-shirts, shows the least environmental impact on this category.

PROCESS CONTRIBUTION

Process contribution is an analysis of the entire or part of the model, showing for each impact category which individual processes have a larger contribution to the final outcome.

In a model of a garment's life cycle, it is not unlikely to find a total of 20.000-30.000 individual processes. When performing a process contribution analysis, all processes could be ordered according to their environmental performances in the chosen impact category. Some of these processes are being repeated for different impact categories such as electricity production, still they can have different resources. Considering the electricity production example, it can be produced from hard coal or brown coal. These would be two different processes in the model that - together with other energy production technologies - would create the energy mix of a country or region.

When performing a process contribution analysis, it is often the case that a few processes are responsible for the vast majority of the environmental impact while many thousands of processes have little impact. In the following (Table 12), the process contributions for 8 impact categories for t-shirt 0300 are shown. For a deeper dive, see Appendix G, where the process contribution for all t-shirts and impact categories are shown. The process contributions analysis is done using ReCiPe 2016 midpoint (H).

Table 12. *Process contributions of the t-shirt 0300. This table indicates the processes with the highest contribution compared to the remaining processes.*

	T-shirt 0300 (Virgin polyester-BC cotton)	**Amount**
	Global Warming Potential (kg CO_2 eq)	
1	Better Cotton - Seed-cotton {BD}| seed-cotton production, conventional | Conseq, U	1.37
2	Heat, district or industrial, other than natural gas {DK}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Conseq, U	0.60
3	Electricity, high voltage {RoW}| electricity production, natural gas, combined cycle power plant | Conseq, U	0.46
4	Electricity, high voltage {RoW}| electricity production, lignite | Conseq, U	0.43
	Land Use (m^2a crop eq)	
1	Wood chips, wet, measured as dry mass {SE}| hardwood forestry, birch, sustainable forest management | Conseq, U	10.47
2	Wood chips, wet, measured as dry mass {SE}| softwood forestry, pine, sustainable forest management | Conseq, U	7.98
3	Wood chips, wet, measured as dry mass {SE}| softwood forestry, spruce, sustainable forest management | Conseq, U	7.74
4	Wood chips, wet, measured as dry mass {DE}| hardwood forestry, beech, sustainable forest management | Conseq, U	5.30
5	Wood chips, wet, measured as dry mass {DE}| softwood forestry, spruce, sustainable forest management | Conseq, U	2.19
6	Wood chips, wet, measured as dry mass {DE}| softwood forestry, pine, sustainable forest management | Conseq, U	1.82
7	Better Cotton - Seed-cotton {BD}| seed-cotton production, conventional | Conseq, U	1.64
	Water Consumption (m^3)	
1	Tap water {Europe without Switzerland}| tap water production, ultrafiltration treatment | Conseq, U	0.70
2	Irrigation {PH}| irrigation, surface | Conseq, U	0.11
3	Irrigation {RoW}| irrigation, surface | Conseq, U	0.08
4	Tap water {RoW}| tap water production, ultrafiltration treatment | Conseq, U	0.06
5	Irrigation {RoW}| irrigation, sprinkler | Conseq, U	0.03
	Freshwater Ecotoxicity (kg 1,4-DCB)	
1	Better Cotton - Seed-cotton {BD}| seed-cotton production, conventional | Conseq, U	0.40

Marine Ecotoxicity (kg 1,4-DCB)		
1	Better Cotton - Seed-cotton {BD}| seed-cotton production, conventional | Conseq, U	0.51
2	Heat, district or industrial, other than natural gas {DK}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Conseq, U	0.04
Terrestrial Ecotoxicity (kg 1,4-DCB)		
1	Heat, district or industrial, other than natural gas {DK}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Conseq, U	58.52
2	Brake wear emissions, lorry {RoW}| treatment of | Conseq, U	20.92
3	Brake wear emissions, lorry {RER}| treatment of | Conseq, U	8.50
Freshwater Eutrophication (kg P eq)		
1	Better Cotton - Seed-cotton {BD}| seed-cotton production, conventional | Conseq, U	0.06
Human Non-carcinogenic Toxicity kg 1,4-DCB)		
1	Wood ash mixture, pure {Europe without Switzerland}| treatment of wood ash mixture, pure, landfarming | Conseq, U	10.82
2	Heat, district or industrial, other than natural gas {DK}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Conseq, U	2.64
No cotton seed - Human Non-carcinogenic Toxicity (kg 1,4-DCB)		
1	Wood ash mixture, pure {Europe without Switzerland}| treatment of wood ash mixture, pure, landfarming | Conseq, U	10.82
2	Heat, district or industrial, other than natural gas {DK}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Conseq, U	2.64
3	Wastewater, average {Europe without Switzerland}| treatment of wastewater, average, capacity 1E9l/year | Conseq, U	0.70

The result of process contribution analysis on Global Warming Potential, Freshwater Ecotoxicity and Freshwater Eutrophication categories show that the most contributing process to the environmental burden is the process of cotton seed production. Producing energy also, is affecting the environment negatively in most of the impact categories. Production of wood ash for plant growth in Human non-carcinogenic (10.82 kg 1,4-DCB, both with and without seed) has the highest contribution to these impact categories. This indicates that the same unit processes have the same contributions and the contribution is not seed connected. Water production for washing the t-shirts in the laundry service (0.70 m^3) in the Water consumption category has the 1st place for impacting the mentioned category negatively.

Overall, these results mean that to produce 1 t-shirt of style 0300, several processes are needed which some of them are provided in Table12, and they affect different parts of the environment.

HOTSPOT ANALYSIS

Hotspot analysis is done indicating the most environmentally impactful stage of the t-shirt production in damaging the environment.

For this purpose, 6 impact categories are chosen that can be seen in Figures 10 to 15. As can be seen in Figure 10, harvest of organic cotton has a negative amount of carbon dioxide release, which means it has a positive impact on the environment - specifically on the Global Warming Potential impact category. This can be explained by the fact that this result obtained by consequential modelling. Running a process contribution indicates that due to more demand for planting cotton, less field for planting soybean seeds is needed (-92.5 %).

High amount of the carbon being emitted throughout the production stages such as Fibre extraction, Yarn production and especially Use and wash phase is coming from how the electricity is being generated.

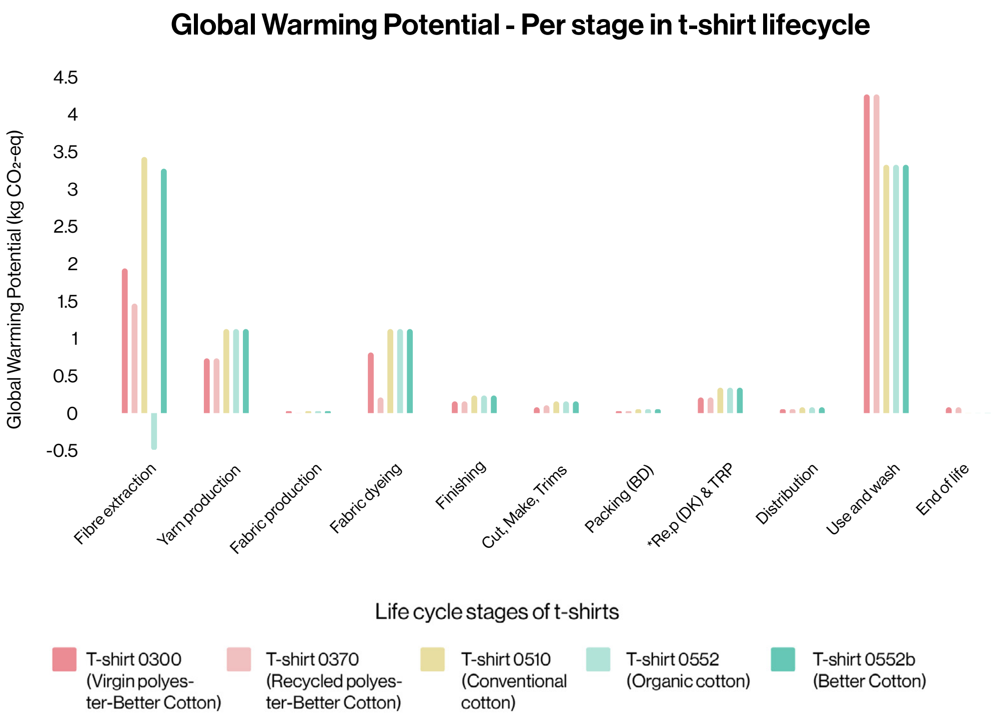

Figure 10. *Hotspot analysis of all t-shirts from cradle-to-grave on the Global Warming Potential impact categories. *Re.p (DK) & TRP is an abbreviation for 'Repacking & transporting to DK'.*

Figure 11 shows the environmental performance of the t-shirts per stage life cycle on the Freshwater Eutrophication impact category. 100% Organic cotton t-shirt (0552) has a noticeable lower environmental impact in the mentioned category. This is due to the absence of chemicals and pesticides that enriches the nutrients. As well, the reason why conventional cotton and Better Cotton's environmental burden is notably high is because of the pesticide use. In relation to the 03 styles, part of the impact is coming from the pesticide used for 60% of the t-shirts. The rest is coming from the chemical used to produce polyester in case of 0300 and to recycle polyester for 0370.

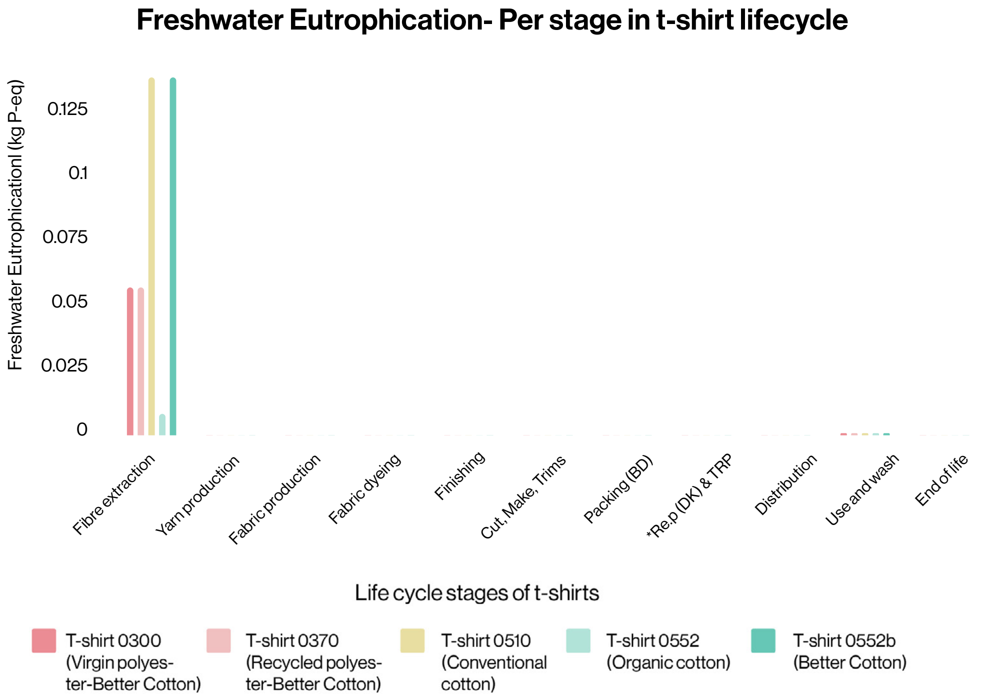

***Figure 11**. Hotspot analysis of all t-shirts from cradle-to-grave on the Freshwater Eutrophication impact categories. *Re.p (DK) & TRP is an abbreviation for 'Repacking & transporting to DK'.*

Regarding the environmental impact of t-shirts on the Land Use category (Figure 12), it is noticeable that the highest impacts are arising from the Fibre Extraction and Use and Wash stages. Obviously, t-shirt 0552 has a higher environmental burden as growing organic cotton occupies more farming land. The high environmental impact from the use phase is due the electricity consumption. Based on the processes' contribution, wood chips are used to produce electricity, and this leads to high forestry activities to produce energy - which eventually leads the woodlands transforming into bare land.

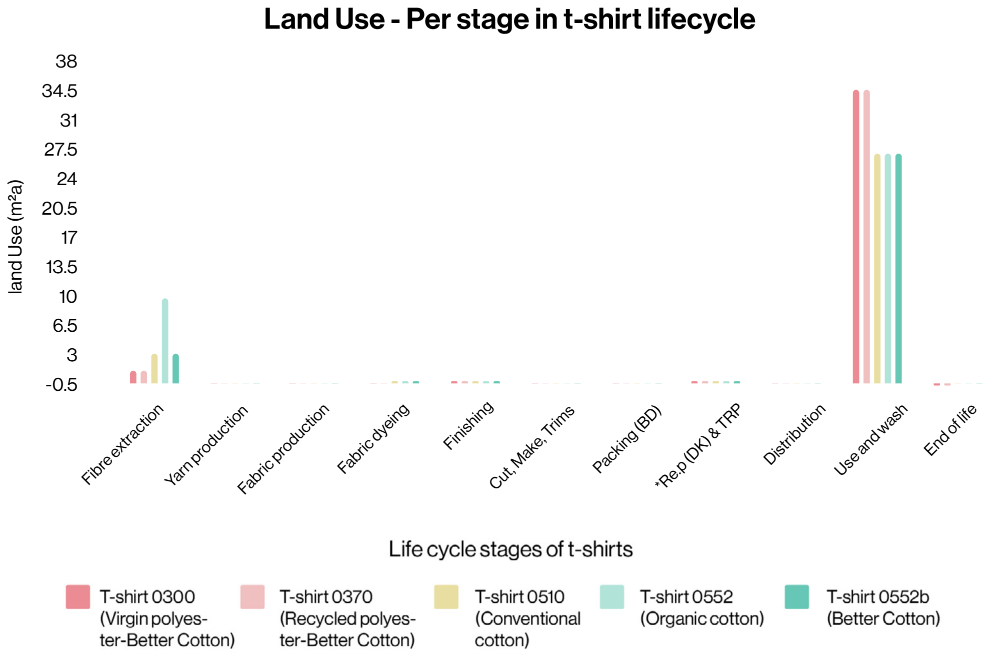

Figure 12. *Hotspot analysis of all t-shirts from cradle-to-grave on the Land Use impact category. *Re.p (DK) & TRP is an abbreviation for 'Repacking & transporting to DK'.*

To grow cotton and produce fibre materials chemicals are being used. Therefore, the early stage of the production has the highest environmental impact on this category. However, as organic cotton uses no chemicals (at least the man-made ones), the environmental impact of this t-shirt is very low compared to the other ones. Interestingly, ID® IDENTITY has a great performance in the fabric dying stage which resulted in a very low environmental burden on the Freshwater Ecotoxicity category. Due to the use of detergents in the wash phase, there can be seen a negative environmental impact arising on this impact category from all t-shirts. Please see Figure 13.

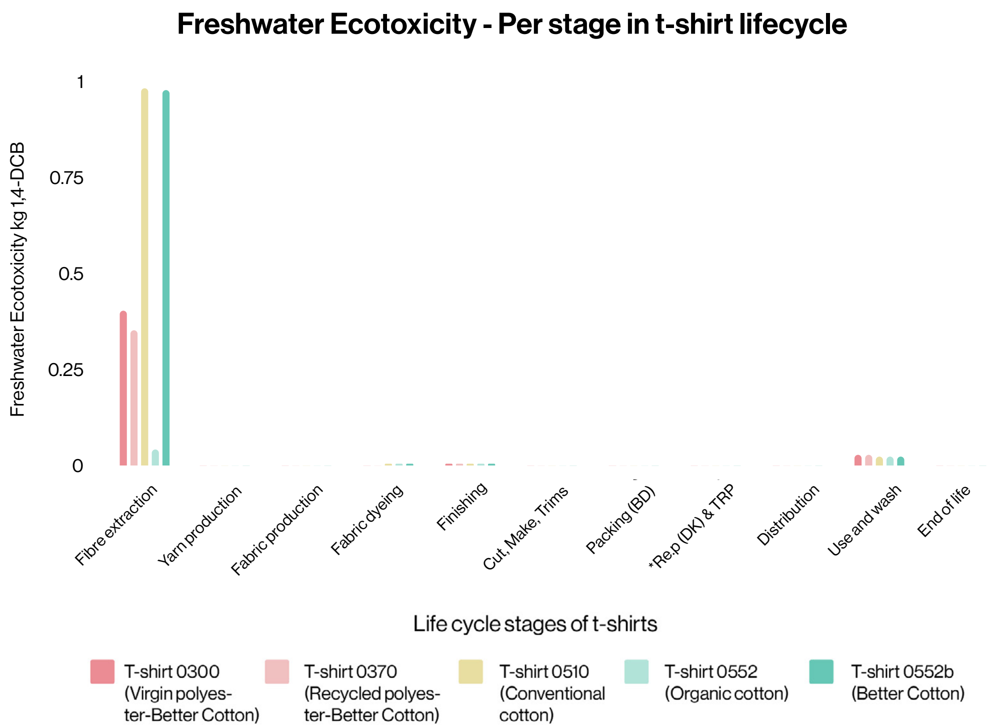

Figure 13*. Hotspot analysis of all t-shirts from cradle-to-grave on the Freshwater Ecotoxicity impact category. *Re.p (DK) & TRP is an abbreviation for 'Repacking & transporting to DK'.*

Figure 14 and 15 indicate the environmental performances of these products on the amount of water being used and the scarcity of water resources. As can be seen, all t-shirts contribute almost the same to these categories, especially on the stages such as fibre extraction and Use and Wash, as well as dyeing fabric.

Figure 15 also, as the environmental impact on Water Scarcity impact category depends on the location, data on Water Scarcity are not generally representative at country level. This introduces an uncertainty across the Life Cycle Inventory.

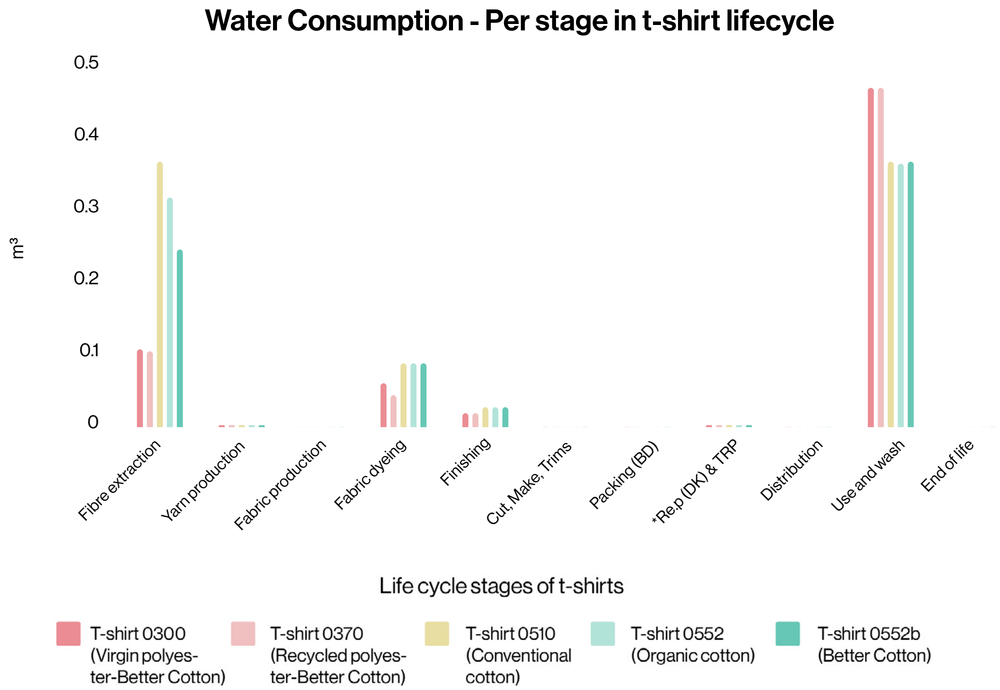

Figure 14. *Hotspot analysis of all t-shirts from cradle-to-grave on the Water Consumption impact category. *Re.p (DK) & TRP is an abbreviation for 'Repacking & transporting to DK'.*

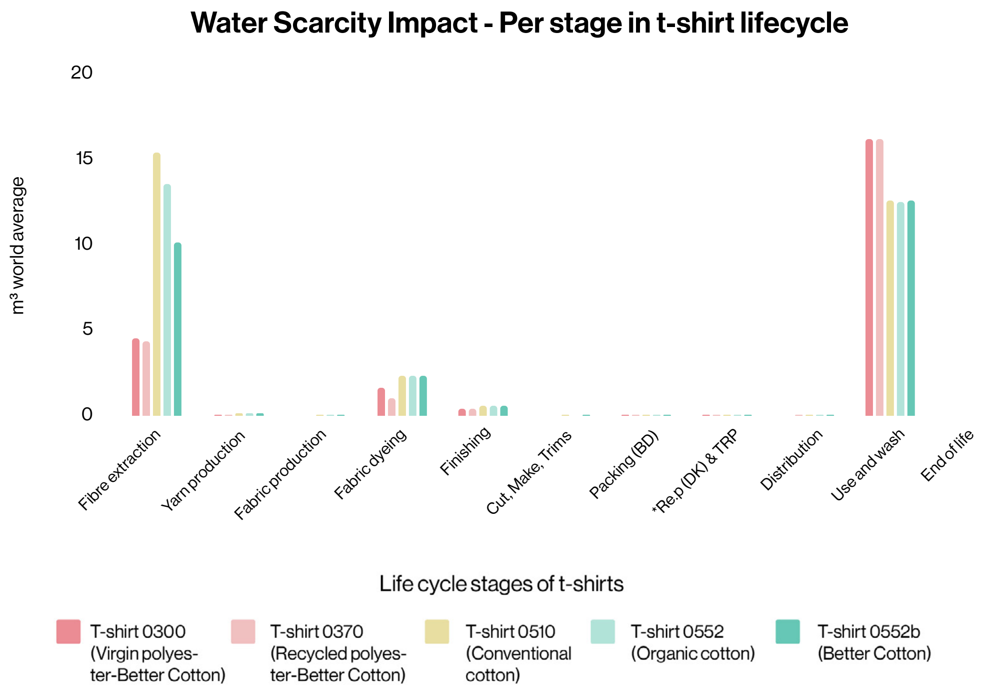

Figure 15. *Hotspot analysis of all t-shirts from cradle-to-grave on the Water Scarcity impact category. *Re.p (DK) & TRP is an abbreviation for 'Repacking & transporting to DK'.*

NORMALISATION

Where characterisation answers the question "How much is the environmental impact?", the normalisation results indicate the magnitude of the impact. It is not trivial to evaluate if a value is high or low when a multitude of numbers with different units is presented. The normalisation attempts to assist in this by relating all the environmental impacts to a fixed factor. This factor is often a year in an average person's life. The result of the analysis will be a set of values showing how high each impact is compared to the impact of one lived life of an average human. The unit for all impact categories will be $person\text{-}years\ (p{*}y)$ or it can be shown in %. A value of 1 person year in Global Warming Potential indicates that the environmental burden of the product, when it comes to Climate Impact, is equal to the amount caused by an average person during one year.

Table 13, shows normalised values for all t-shirts.

The normalised results indicate that the most of the environmental pressure coming from the t-shirts is on the Freshwater Eutrophication; especially from conventional and Better Cotton cotton. The magnitude of the environmental impact on Human Non-carcinogenic Toxicity and Mineral Resource Scarcity and Ionizing Radiation, however, is in order lower on these categories.

__Table 13__. Normalised result of the 5 t-shirts, at midpoint level for 18 impact categories. Values can only be read horizontally.

		Virgin polyester -Better Cotton	Recycled polyester -Better Cotton	Conven-tional cotton	Organic cotton	Better Cotton
Impact category	**Unit**	**T-shirt 0300**	**T-shirt 0370**	**T-shirt 0510**	**T-shirt 0552**	**T-shirt 0552b**
Global Warming Potential	person*year	1.04E-03	9.04E-04	1.22E-03	7.32E-04	1.21E-03
Stratospheric Ozone Depletion		1.16E-03	1.04E-03	2.08E-03	6.34E-04	2.07E-03
Ionizing Radiation		6.39E-05	6.04E-05	6.01E-05	5.44E-05	5.93E-05
Ozone Formation, Human Health		3.84E-03	3.75E-03	3.24E-03	3.08E-03	3.22E-03
Fine Particulate Matter Formation		1.08E-03	1.00E-03	1.22E-03	8.67E-04	1.20E-03
Ozone Formation, Terrestrial Ecosystems		4.48E-03	4.37E-03	3.78E-03	3.60E-03	3.76E-03
Terrestrial Acidification		2.14E-03	2.07E-03	2.60E-03	1.60E-03	2.57E-03
Freshwater Eutrophication		9.02E-02	9.01E-02	2.18E-01	1.44E-02	2.18E-01
Marine Eutrophication		2.06E-02	2.06E-02	4.94E-02	4.32E-03	4.94E-02
Terrestrial Ecotoxicity		6.11E-03	5.99E-03	5.08E-03	4.74E-03	5.06E-03
Freshwater Ecotoxicity		1.76E-02	1.55E-02	4.07E-02	3.20E-03	4.06E-02
Marine Ecotoxicity		1.36E-02	1.27E-02	3.03E-02	3.14E-03	3.02E-02
Human Carcinogenic Toxicity		3.99E-03	4.40E-03	2.51E-03	4.46E-03	2.41E-03
Human Non-carcinogenic Toxicity		-6.25E-04	-6.34E-04	-2.30E-03	3.51E-04	-2.30E-03
Land Use		5.88E-03	5.87E-03	5.02E-03	6.04E-03	5.02E-03
Mineral Resource Scarcity		5.44E-07	3.70E-07	1.17E-06	2.94E-07	1.12E-06
Fossil Resource Scarcity		2.47E-03	2.18E-03	2.50E-03	1.95E-03	2.45E-03
Water Consumption		2.50E-03	2.43E-03	3.25E-03	3.06E-03	2.79E-03

WEIGHTING

Weighting can be seen as an extension of normalisation. While normalisation is answering the question “is that much?”, weighting is answering the question “is that important?”. The intent is to help the reader understand which impact categories are more important and in turn prioritise efforts. There is some debate on the topic of weighting, and some are arguing that weighting introduces a level of subjectivity into the analysis since there is no scientific basis for scoring some impact categories above others. On the other hand, others argue that there are introductions on subjectivity in the LCA process as soon as it begins, since choices of methodologies, data and other modelling choices affect the result.

There are several ways of performing weighting. They have different entry points and are therefore likely to give different results. The three methods chosen in this study are:

Environmental prices

This method is introducing monetary units to the model. It represents the willingness-to-pay to prevent a certain impact. The price differs per region and per country and the unit is a monetary value per kg of emission (CE Delft, 2022).

The result of the Environmental prices method is shown in Table 14.

Table 14. *Weighted result of the 5 t-shirts, using Environmental Price methodology, on different impact categories. Values can also be read both horizontally and vertically.*

		Virgin polyester -Better Cotton	Recycled polyester -Better Cotton	Conven-tional cotton	Organic cotton	Better Cotton
Impact category	**Unit**	**T-shirt 300**	**T-shirt 370**	**T-shirt 510**	**T-shirt 552**	**T-shirt 552b**
Total	EUR2015	1.35E+01	1.33E+01	1.43E+01	1.10E+01	1.42E+01
Climate Change		4.51E-01	3.93E-01	5.27E-01	3.19E-01	5.18E-01
Ozone Depletion		1.53E-04	1.20E-04	2.69E-04	9.08E-05	2.18E-04
Terrestrial Acidification		9.28E-01	9.00E-01	1.10E+00	7.05E-01	1.09E+00
Freshwater Eutrophication		1.14E-01	1.14E-01	2.71E-01	1.99E-02	2.71E-01
Marine Eutrophication		1.03E+00	1.03E+00	2.44E+00	2.25E-01	2.44E+00
Human Foxicity		2.92E-01	2.90E-01	1.61E-01	2.71E-01	1.55E-01
Photochemical Oxidant Formation		1.87E-01	1.82E-01	1.58E-01	1.49E-01	1.57E-01
Particulate Matter Formation		2.62E+00	2.46E+00	2.81E+00	2.11E+00	2.78E+00
Terrestrial Ecotoxicity		3.61E+00	3.62E+00	3.37E+00	3.49E+00	3.37E+00
Freshwater Ecotoxicity		7.65E-03	5.37E-03	1.47E-02	3.04E-03	1.47E-02
Marine Ecotoxicity		1.13E-03	6.78E-04	2.44E-03	3.05E-04	2.43E-03
Ionising Radiation		1.08E-02	1.03E-02	9.96E-03	8.79E-03	9.88E-03
Agricultural Land Occupation		4.22E+00	4.21E+00	3.41E+00	3.63E+00	3.41E+00
Urban Land Occupation		3.89E-02	3.84E-02	3.18E-02	3.01E-02	3.17E-02

Environmental Footprint

This weighting method has been compiled by the network of LCA experts. The objective has been to order the impact categories according to their relevance to the overall environmental problems (Sala et al., 2018).

The result of the Environmental prices method is shown in Table 15.

Table 15: *Weighted result of the 5 t-shirts, using Environmental Footprint methodology, on different impact categories. Values can also be read both horizontally and vertically.*

		Virgin polyester -Better Cotton	Recycled polyester -Better Cotton	Conven-tional cotton	Organic cotton	Better Cotton
Impact category	**Unit**	**T-shirt 300**	**T-shirt 370**	**T-shirt 510**	**T-shirt 552**	**T-shirt 552b**
Total	mPt	4.27E+00	4.15E+00	7.09E+00	2.21E+00	7.03E+00
Climate Change		2.17E-01	1.89E-01	2.56E-01	1.53E-01	2.52E-01
Ozone Depletion		1.45E-03	1.15E-03	2.33E-03	9.04E-04	1.88E-03
Ionising Radiation		2.71E-03	2.59E-03	2.50E-03	2.20E-03	2.48E-03
Photochemical Ozone Formation		1.00E-01	9.79E-02	8.55E-02	8.01E-02	8.48E-02
Particulate Matter		2.63E-01	2.57E-01	2.68E-01	2.03E-01	2.68E-01
Human Toxicity, Non-cancer		-1.47E-01	2.04E-02	-4.17E-01	1.26E-02	-4.19E-01
Human Toxicity, Cancer		3.40E-02	5.89E-02	5.79E-02	1.66E-02	5.76E-02
Acidification		1.63E-01	1.58E-01	1.92E-01	1.24E-01	1.90E-01
Eutrophication, Freshwater		1.02E+00	1.02E+00	2.47E+00	1.62E-01	2.46E+00
Eutrophication, Marine		5.34E-01	5.33E-01	1.20E+00	1.41E-01	1.20E+00
Eutrophication, Terrestrial		1.35E-01	1.33E-01	1.50E-01	1.06E-01	1.49E-01
Ecotoxicity, Freshwater		8.24E-01	5.88E-01	1.13E+00	4.69E-01	1.12E+00
Land Use		3.91E-01	3.90E-01	3.20E-01	3.49E-01	3.20E-01
Water Use		1.76E-01	1.70E-01	2.38E-01	2.23E-01	1.99E-01
Resource Use, Fossils		1.35E-01	1.19E-01	1.36E-01	1.07E-01	1.34E-01
Resource Use, Minerals and Metals		4.20E-01	4.17E-01	1.01E+00	6.30E-02	1.00E+00

No seed-cotton production process

Table 16 and 17 are the results for both weighting methods, excluding the cotton seed production process.

***Table 16**: Weighted result of the 5 t-shirts, using Environmental Prices methodology, on different impact categories, excluding cotton seed production process. Values can also be read both horizontally and vertically.*

		Virgin polyester -Better Cotton	Recycled polyester -Better Cotton	Conven-tional cotton	Organic cotton	Better Cotton
Impact category	**Unit**	**T-shirt 0300**	**T-shirt 0370**	**T-shirt 0510**	**T-shirt 0552**	**T-shirt 0552b**
Total	EUR2015	1.18E+01	1.15E+01	9.98E+00	9.98E+00	9.99E+00
Climate Change		3.46E-01	2.96E-01	2.61E-01	2.67E-01	2.61E-01
Ozone Depletion		9.84E-05	8.58E-05	8.62E-05	8.66E-05	8.62E-05
Terrestrial Acidification		7.14E-01	6.91E-01	5.66E-01	5.66E-01	5.66E-01
Freshwater Eutrophication		3.95E-03	3.83E-03	2.43E-03	2.55E-03	2.44E-03
Marine Eutrophication		4.26E-02	4.16E-02	3.35E-02	3.37E-02	3.35E-02
Human Toxicity		3.38E-01	3.29E-01	2.69E-01	2.69E-01	2.69E-01
Photochemical Oxidant Formation		1.80E-01	1.76E-01	1.40E-01	1.41E-01	1.40E-01
Particulate Matter Formation		2.27E+00	2.13E+00	1.92E+00	1.92E+00	1.93E+00
Terrestrial Ecotoxicity		3.66E+00	3.66E+00	3.49E+00	3.49E+00	3.49E+00
Freshwater Ecotoxicity		2.57E-03	2.51E-03	2.27E-03	2.31E-03	2.27E-03
Marine Ecotoxicity		2.04E-04	1.93E-04	1.65E-04	1.67E-04	1.65E-04
Ionising Radiation		1.03E-02	9.83E-03	8.63E-03	8.58E-03	8.60E-03
Agricultural Land Occupation		4.16E+00	4.15E+00	3.26E+00	3.24E+00	3.26E+00
Urban Land Occupation		3.82E-02	3.77E-02	3.00E-02	2.99E-02	3.00E-02

Table 17: *Weighted result of the 5 t-shirts, using Environmental Footprint methodology, on different impact categories, excluding cotton seed production process. Values can also be read both horizontally and vertically.*

		Virgin polyester -Better Cotton	Recycled polyester -Better Cotton	Conven-tional cotton	Organic cotton	Better Cotton
Impact category	**Unit**	**T-shirt 0300**	**T-shirt 0370**	**T-shirt 0510**	**T-shirt 0552**	**T-shirt 0552b**
Total	mPt	2.06E+00	1.99E+00	1.64E+00	1.64E+00	1.64E+00
Climate Change		1.65E-01	1.41E-01	1.24E-01	1.27E-01	1.24E-01
Ozone Depletion		1.03E-03	9.12E-04	8.49E-04	8.55E-04	8.49E-04
Ionising Radiation		2.58E-03	2.47E-03	2.16E-03	2.15E-03	2.16E-03
Photochemical Ozone Formation		9.66E-02	9.44E-02	7.55E-02	7.55E-02	7.55E-02
Particulate Matter		2.27E-01	2.21E-01	1.79E-01	1.78E-01	1.78E-01
Human Toxicity, Non-cancer		3.53E-02	3.41E-02	2.61E-02	2.65E-02	2.61E-02
Human Toxicity, Cancer		1.50E-02	1.42E-02	1.12E-02	1.14E-02	1.12E-02
Acidification		1.26E-01	1.22E-01	1.00E-01	1.00E-01	1.00E-01
Eutrophication, Freshwater		1.01E-02	8.98E-03	1.80E-03	3.03E-03	1.84E-03
Eutrophication, Marine		6.04E-02	5.91E-02	4.73E-02	4.74E-02	4.73E-02
Eutrophication, Terrestrial		1.08E-01	1.05E-01	8.18E-02	8.23E-02	8.18E-02
Ecotoxicity, Freshwater		5.29E-01	5.16E-01	3.99E-01	4.02E-01	3.99E-01
Land Use		3.82E-01	3.82E-01	2.99E-01	2.98E-01	2.99E-01
Water Use		1.46E-01	1.41E-01	1.27E-01	1.26E-01	1.27E-01
Resource Use, Fossils		1.22E-01	1.09E-01	1.02E-01	1.02E-01	1.02E-01
Resource Use, Minerals and Metals		3.56E-02	3.50E-02	6.15E-02	6.16E-02	6.15E-02

It turned out that the seed cotton process was giving unreliable results due to the way that it was constructed in the database. This caused uncertainties, and the problem was investigated together with the external reviewer. Together with the external reviewer, it was decided to test the robustness of the results by calculating the results omitting the cotton seed production process. The result showed that only the human non-carcinogenic toxicity should be deemed unreliable.

TEKSTIL REVOLUTIONEN

INTERPRETATION

The Life Cycle Interpretation section of the report focusses on interpreting the resuls in the LCIA.

SIGNIFICANT ISSUES

The study focuses on analysing the environmental performances of four actual t-shirts and one imaginary one, on 18 environmental impact categories. The t-shirts are divided into two styles 03 (0300 and 0370) and 05 (0510, 0552 and 0552b). To model and analyse their impact, some data are collected and for the rest of information with no data, some assumptions were made that can be found in Appendix D. Considering t-shirts style 03, 0370 has a lower environmental impact on most of the impact categories. However, it has a high environmental burden on the Land Use category due to cotton production and energy production from wood chips. Based on the weighted results, this style has an environmental impact on Terrestrial Ecotoxicity and Agricultural Land Occupation (EUR2015).

Among t-shirts style 05, 0510 is made of 100% organic cotton and has the overall lowest environmental pressure. The Freshwater Eutrophication impact category (mPt) of the weighted result is the most affected category by t-shirts with conventional cotton (0552) and Better Cotton (0552b).

When the t-shirts are disposed, they are incinerated.

EVALUATION

Completeness checks

To determine how complete our available data within our collected data and the results are, a completeness check is made. It covers the interaction between the first 3 steps of LCA, Goal definition, Scope definition, and Life Cycle Inventory.

This study is conducted considering the life cycle of all t-shirts from cradle-to-grave. The t-shirts are incinerated at the end of life. The collected data met the requirements in the Goal and Scope. System boundary coverage in terms of elementary flows, process coverage and product & waste flow met the requirements of the completeness check. Also, negligible flows are taken out.

This study, included 4 existing and one imaginary t-shirts and each of them consist

of a large inventory table. However, not all the data could be found in the Ecoinvent database and for some production stages, such as fibre extraction and the use phase. Regarding the former stage, therefore, the closest database is chosen and for the latter stage, the data is obtained from the report Sandin, *et al.*, (2019).
The functional unit for the t-shirts are based on the use of one t-shirt, calculated based on the number of washes. Since the functional unit is defined similarly for all 5 t-shirts, the reference flows could be considered as fair comparison. This means that the environmental impacts of the t-shirts could be compared with each other.

SENSITIVITY CHECK

Sensitivity analysis

The purpose of a sensitivity analysis is to show how sensitive the final results are to a single or set of parameters. There are two levels to this analysis. One level is to identify how significant a change in the model is for the final results. The next level is identifying whether the changes are important for the conclusions.

There are two reasons for doing a sensitivity analysis:

1. To get more robust results
2. For testing scenarios or scenario analysis of versions of the model that is made.

The latter could be to test the effect of replacing renewable energy to a facility, changing the transport route, or even changing a supplier. This is called scenario analysis and does often consist of substituting one process in each run in the existing model.

In practice, sensitivity analysis is done by changing the data of the model and analysing the results through the following equation:

$$S_{in} = \frac{(\triangle output / \triangle output)}{(\triangle input_n / \triangle input_n)}$$

S_{in} is the sensitivity coefficient that will show a change in input affects the output. Here, the change of the input is focused on a single process while the output is focused on the final results. Thereby, it shows how much a change in a single process changes the final outputs. Normally, when S_{in} is larger than 0.3, it will be seen as a sensitive parameter.

In the following figures, S_{in} values for the tested parameters, both on minimum (Figure 16) and maximum (Figure 17) number of washes is indicated.

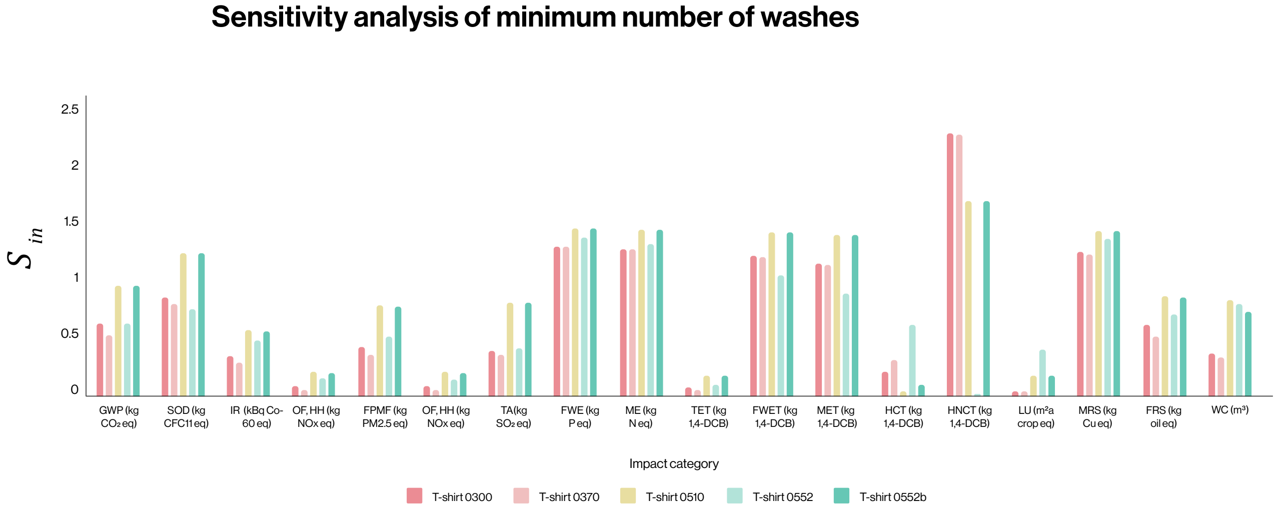

Figure 16*. Sensitivity analysis ,analysing the minimum (150 and 75 for t-shirts style 03 and 05, respectively) number of washes.*

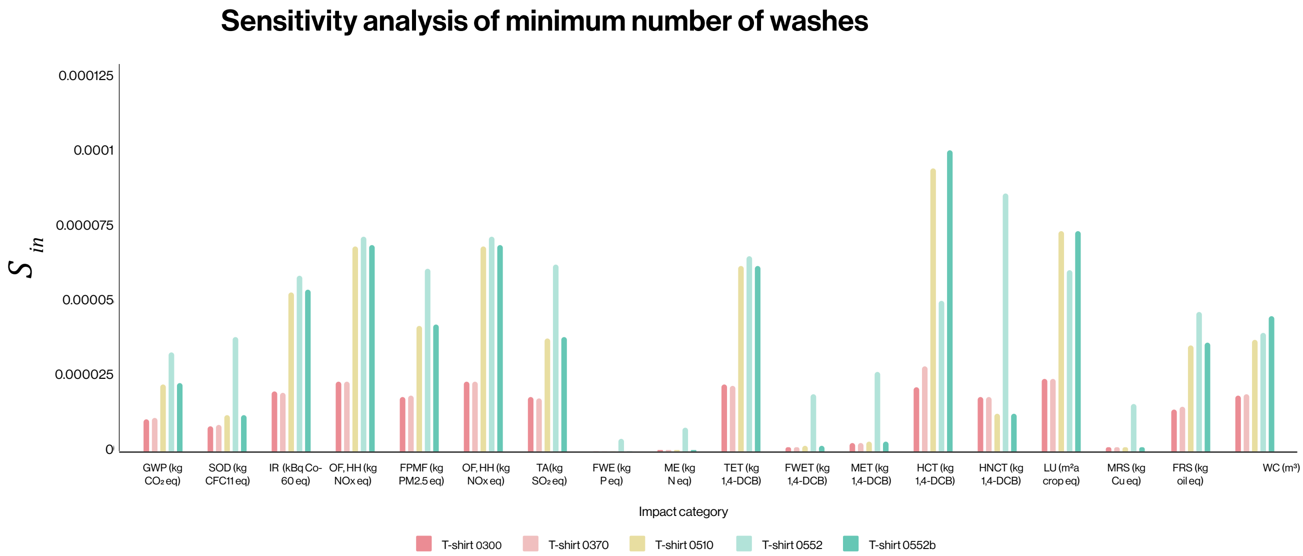

Figure 17. *Sensitivity analysis ,analysing the minimum (250 and 150 for t-shirts style 03 and 05, respectively) number of washes.*

The graphs above show the difference in the total of each impact category based on changing the number of times that the t-shirts are being washed. The higher the bars on the graphs are, the more significant the change is.

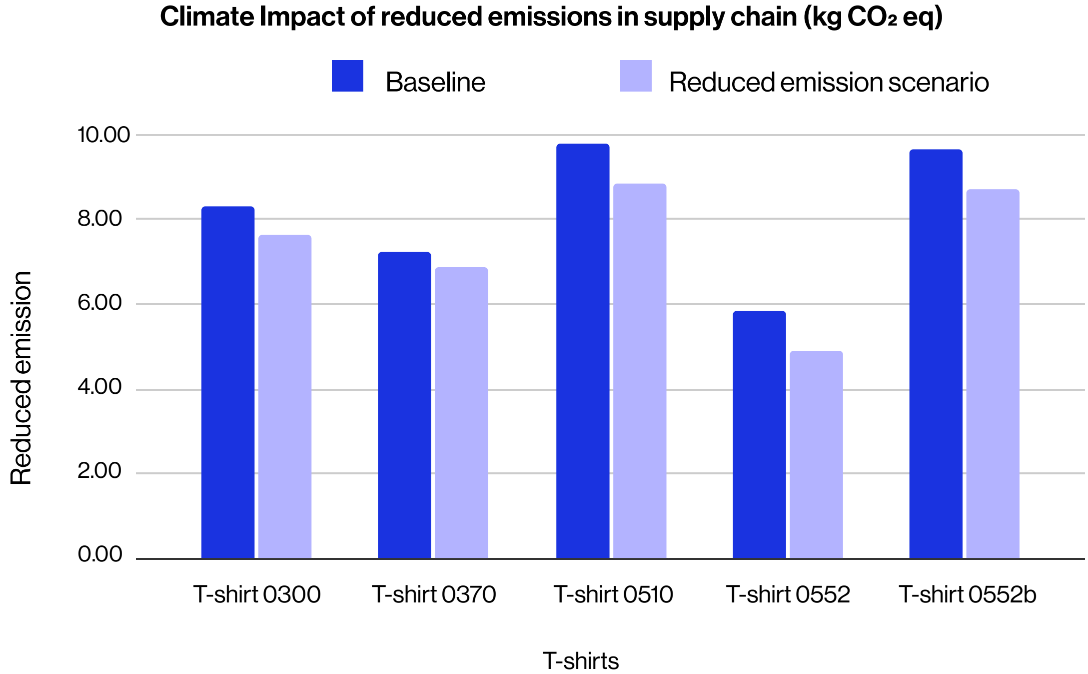

Figure 18. *Climate Impact of the supplier from substituting the fossil fuel-based energy to renewable energy*

Sensitivity analysis is also done on the energy reduction and its impact on the Climate Impact category as requested by ID® IDENTITY (Figure 18). The results from reducing the Climate Impact to half of the value for all the production processes between knitting and packing (including both) show reduction of the overall impacts at 5-16% on climate.

Scenario analysis is also done by applying the relative change formula and it is done by changing a process of the model and analysing the results:

$$r\% = \frac{baseline}{\triangle\, output} \quad or \quad \frac{\triangle\, output}{Baseline}$$

where $r\%$ is the factor for relative change, in absolute values. To use the left-sided equation, the $baseline$ value should be bigger than the value, and to use the right-sided equation is the $\triangle\, output$ value should be bigger than the $baseline$ value.

Scenarios

The baseline for this calculation is considered the actual impact of each t-shirt. For this analysis the following scenarios are considered:

Washing scenario
For the present study, we have made scenarios to evaluate the change in impact for certain conditions. One of these conditions was the number of times that the t-shirts were being washed. Together with the commissioner, it was decided that the mixed fibred t-shirts would have an average number of 200 wash times. This came from a range between 150 and 250. Similarly, the 100% cotton t-shirts were estimated to dure an average of 110 washes, coming from a range of 75 to 150. Creating these scenarios, it is clear that the number of washing times is very high. When the number of washings change, the number of products needed to fulfil the functional unit of 200 wears changes. This means that for example if t-shirt 300 goes from an average of 200 washes to the minimum of 150 washes, there is a need for 1.3 t-shirts (instead of 1 piece) to fulfil 200 wears. Going the other way, and washing the t-shirt 300 for 250 times rather than 200 times, there is only a need for 0.8 t-shirts to fulfil the need. Note here, that it is estimated that the t-shirts made with virgin and recycled polyester last the same number of washes. With more accurate data from the laundry services, this could possibly change conclusions.

The result of the washing scenarios can be found in Table 18.

***Table 18**. The difference (%) between the baseline scenario and the maximum washing cycles scenario.*

% Change from baseline to max wash scenario						
Impact category	**Unit**	**T-shirt 0300**	**T-shirt 0370**	**T-shirt 0510**	**T-shirt 0552**	**T-shirt 0552b**
Global Warming Potential	kg CO2 eq	-9.71%	-8.20%	-17.71%	-11.68%	-17.57%
Stratospheric Ozone Depletion	kg CFC11 eq	-13.14%	-12.38%	-22.80%	-13.81%	-22.77%
Ionizing Radiation	kBq Co-60 eq	-5.39%	-4.55%	-10.60%	-9.01%	-10.39%
Ozone Formation, Human Health	kg NOx eq	-1.47%	-1.01%	-3.94%	-2.87%	-3.79%
Fine Particulate Matter Formation	kg PM2.5 eq	-6.63%	-5.62%	-14.52%	-9.60%	-14.31%
Ozone Formation, Terrestrial Ecosystems	kg NOx eq	-1.46%	-1.01%	-3.92%	-2.85%	-3.77%
Terrestrial Acidification	kg SO2 eq	-6.18%	-5.70%	-14.96%	-7.71%	-14.83%
Freshwater Eutrophication	kg P eq	-19.78%	-19.78%	-26.67%	-25.34%	-26.67%
Marine Eutrophication	kg N eq	-19.48%	-19.47%	-26.53%	-24.17%	-26.53%
Terrestrial Ecotoxicity	kg 1,4-DCB	-1.37%	-1.00%	-3.46%	-1.92%	-3.38%
Freshwater Ecotoxicity	kg 1,4-DCB	-18.69%	-18.51%	-26.17%	-19.29%	-26.17%
Marine Ecotoxicity	kg 1,4-DCB	-17.67%	-17.50%	-25.67%	-16.34%	-25.67%
Human Carcinogenic Toxicity	kg 1,4-DCB	-3.38%	-4.92%	0.74%	-11.38%	1.82%
Human Non-carcinogenic Toxicity	kg 1,4-DCB	-34.75%	-34.52%	-30.93%	0.43%	-30.93%
Land Use	m2a crop eq	-0.81%	-0.78%	-3.38%	-7.43%	-3.38%
Mineral Resource Scarcity	kg Cu eq	-19.15%	-18.75%	-26.35%	-25.13%	-26.33%
Fossil Resource Scarcity	kg oil eq	-9.53%	-8.12%	-16.01%	-13.00%	-15.80%
Water Consumption	m3	-5.76%	-5.34%	-15.39%	-14.73%	-13.50%

Taking for example the Climate Impact, the maximum use scenario, shows that there is a possibility to save between about 8 and 18% of the Climate Impact from extending the use phase. These results fit the following logic:

By extending the life time of the products by 20-35%, saving the production of the same amount of t-shirts, we save these percentages on the production stage. Given the fact that around half of the Climate Impact comes from the use phase (which remains the same, since there is still a need for one wash per wear), the overall saving is around half of the percentual extension.

This pattern, of course, changes for the different impact categories, since the use phase accounts for a higher or lower fraction of the total impact depending on the impact category.

Consider a category such as Freshwater Ecotoxicity or Marine Ecotoxicity, where the majority of the impact is located in the production stages (especially when

disregarding the organic t-shirt). Here, the potential for reducing the total impact in this category by extending the life cycle is very high, as seen in Table 18.
The Human non-carcinogenic category stands out due to the pesticide use in the Better Cotton and conventional cotton production, as well as the refining of petroleum to make or recycle polyester. A very tiny fraction of this impact comes from the use phase.

Taking, for example, water consumption into consideration, the impact of this category comes overwhelmingly from firstly the use phase and secondly the cotton production. Therefore, the benefits of extending the life time will not affect this category significantly.

Climate Impact from the Main Manufacturing Facility
The supplier in charge of everything from - knitting to packing of the finished products - has made a plan to reduce their overall greenhouse gas emissions by 50% by 2030. To test the significance of this action in the final results, the total impact has been divided into life cycle stages and the climate impact of the stages belonging to the stages under the supplier has been cut in half. The results as shown below indicate that a halving in the Climate Impact of all processes from the knitting to the packaging would create a reduction of the total carbon emissions between 5 and 16% depending on the t-shirt style (Table 19).

The impacts of the stages managed by the supplier accounts for between 9% and up to 32%. This deems it a quite significant actor to engage with. It is important to note that these results only apply for the Climate Impact, since that is the focus of the plan of the supplier.

Table 19: *The result of Climate Impact from production (%) compared to the baseline*

T-shirt	Baseline	Climate Impact of supplier	% of supplier impact	Kg CO_2 eq of green production	Reduced emission scenario	Reduction %	% of baseline
T-shirt 0300	8.29	1.30	16%	0.6338943	7.66	-8%	92%
T-shirt 0370	7.23	0.68	9%	0.33858785	6.89	-5%	95%
T-shirt 0510	9.80	1.87	19%	0.93575215	8.86	-10%	90%
T-shirt 0552	5.85	1.86	32%	0.92917118	4.92	-16%	84%
T-shirt 0552b	9.65	1.88	19%	0.93767215	8.71	-10%	90%

Number of times the t-shirts are used

There is an overlap between sensitivity and uncertainty analysis, when it comes to the number of times that the t-shirts can be used. Collecting more accurate data from the laundries cannot be solved within the time scope of this study. Instead, the issue has been solved by making best-case, worst case and most realistic scenarios with the combined knowledge of the commissioner, the laundry responsible and the practitioner.

Uncertainty analysis

Monte Carlo Analysis

The Monte Carlo Analysis is a standard way of analysing the robustness of data within the realm of "numerical uncertainty propagation". Basically, it is used to narrow down the uncertainty of the results, based on the collected information on the variation of the data.

Although robustness is defined as if the results are above ±95%, based on the critical reviewer experience, the results ranging between ±80% and ±100% are considered robust.

Figures 19, 20 and 21 indicate the result of Monte Carlo on the 5 t-shirts (Midpoint Hierarchy of ReCiPe 2016), comparing them two by two among all 18 impact categories. Each horizontal grid line that parallels the x-axis represents one impact category in the following order:

	Impact category	Abbreviation
1	Water Consumption	WC
2	Fossil Resource Scarcity	FRS
3	Mineral Resource Scarcity	MRS
4	Land Use	LU
5	Human Non-carcinogenic Toxicity	HNCT
6	Human Carcinogenic Toxicity	HCT
7	Marine Ecotoxicity	MET
8	Freshwater Ecotoxicity	FWET
9	Terrestrial Ecotoxicity	TET
10	Marine Eutrophication	ME
11	Freshwater Eutrophication	FWE
12	Terrestrial Acidification	TA
13	Ozone Formation, Terrestrial Ecosystems	OF,TE
14	Fine Particulate Matter Formation	FPMF
15	Ozone Formation, Human Health	OF,HH
16	Ionizing Radiation	IR
17	Stratospheric Ozone Depletion	SOD
18	Global Warming Potential	GWP

The left side of the graph (blue bars) indicates A<B, meaning that the product A compared to product B, has lower or is likely to have a lower environmental burden on the mentioned impact categories. On the other hand, the right side of the graph illustrating the orange bars, explains that A>=B, which means product A has higher or likely to have a higher damage on the relevant impact categories compared to product B.

Figure 19 shows the uncertainty results of t-shirts 300 (A) and 370 (B). As can be seen, most of the bars are lying towards the right side of the chart, mostly above 80%. This means that the results on the environmental performance of these t-shirts are robust in 12 out of 18 impact categories. T-shirt 0300 has higher environmental impact on these 12 categories, and has most likely higher impact also on the rest 5 categories (MET 75%, LU 65.5%, HNC 60%, WC 55%, and FWE 50.5%). ME having 50% of results, however, it is limiting the interpretation to claim that the impact on this category attributes to any specific t-shirt.

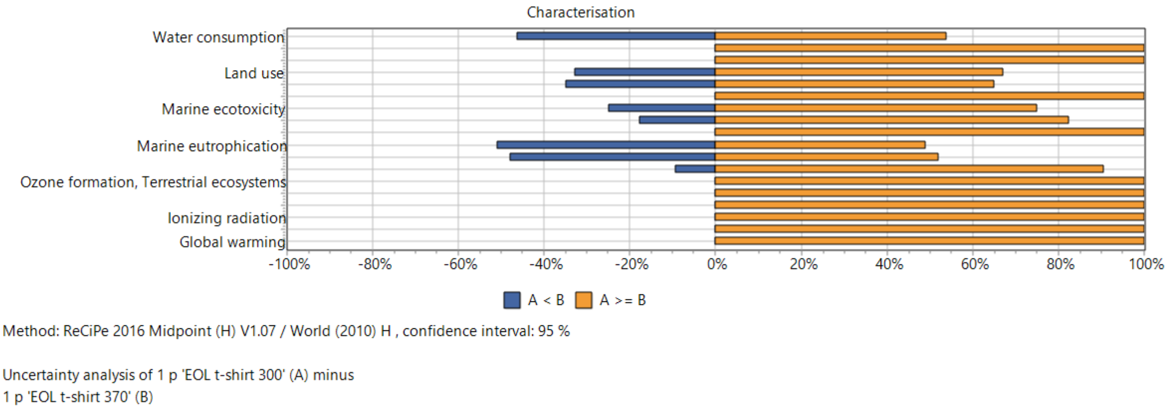

Figure 19. *The uncertainty results for t-shirts 0300 and 0370*

The uncertainty results for t-shirts 0510 (A) and 0552b (B) are shown in Figure 20. These t-shirts show very low robustness in most of the impact categories (many of the bars are not conclusively on one side or the other). This means that it cannot be stated which t-shirt has the highest environmental burden on most of the impact categories.

Only 4 impact categories, namely WC, FFRS, IR and MRS with a % of ≈100%, ≈ 98%, ≈ 98%, and ≈95.5%, respectively show robust results; meaning that t-shirt 0510 has a higher environmental impact on them. This t-shirt is probably a bigger burden on the impact categories, but ME, FWE and SOD; as they are more likely to be influenced by t-shirt 0552. The results on the categories MET and FWET with 50% of uncertainty, make it impossible to attribute which t-shirts have more serious damage in the mentioned categories.

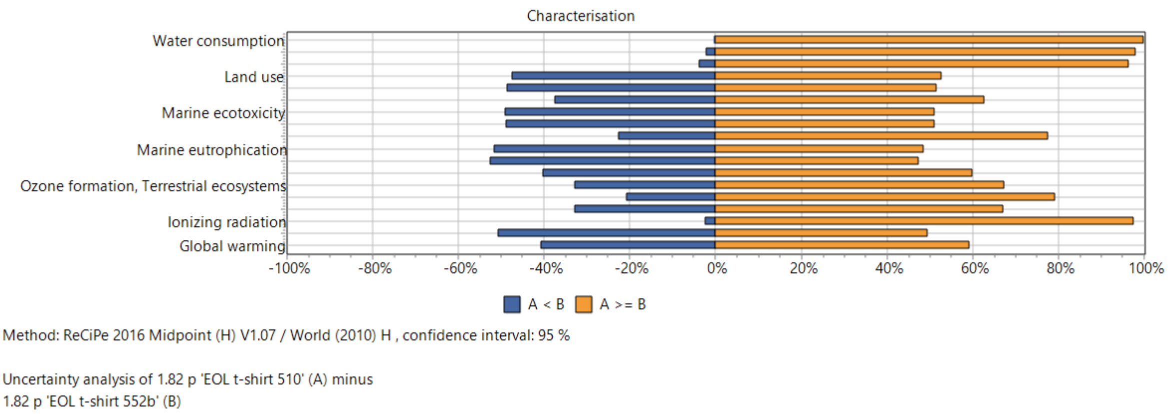

Figure 20*. The uncertainty results for t-shirts 0510 and 0552b*

Comparing t-shirt 0510 with 0552 in Figure 21, the results appear to be robust in 16 impact categories. The only categories with high uncertainty are WC with about 55% and HCT with almost 40%. The result of the former category shows that the t-shirt 0510 has a higher chance to affect water consumption and the latter is probably affected by t-shirt 0552. LU and HNCT categories with a percentage of more than -100%, are highly affected by t-shirt 0510. The rest of the categories, with a minimum of almost 90%, are all affected by t-shirt 0552.

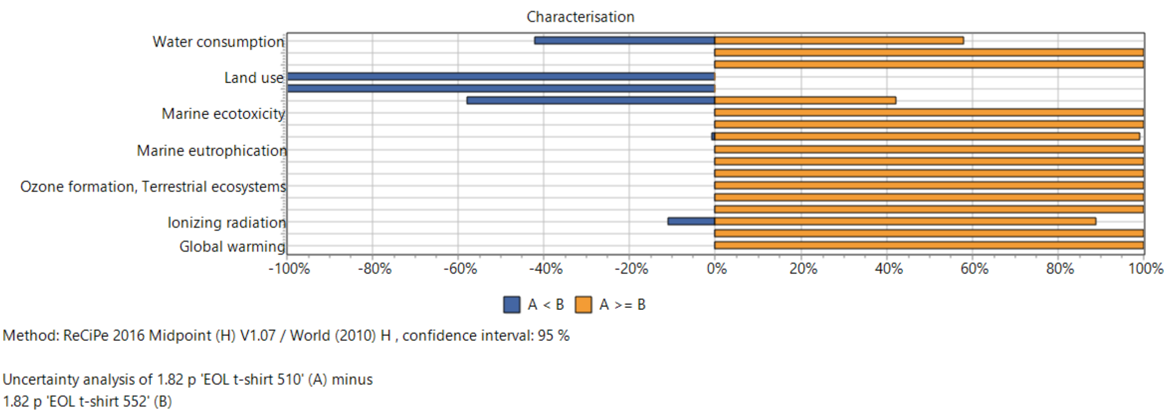

Figure 21*. The uncertainty results for t-shirts 0510 and 0552*

Overall, it can be concluded that the results of the environmental impact, when comparing t-shirt 0300 to 0370, and 0510 to 0552 are robust in most of the impact categories. However, when it comes to comparing 0510 to 0522b, it is not possible to state which t-shirt has higher environmental harm among most of the impact categories.

Consistency checks

The objective of the consistency check is to make sure that there is alignment between the quality of data collected and the significance of processes.That is to say that processes that are highly significant to the results and the conclusions should have a higher degree of data quality to make the study as robust as possible.

The consistency check is performed after the data analysis is done to indicate the interaction between the previous stage and the Life Cycle Impact Assessment (LCIA) stage. This is because it is at the LCIA stage that the insight into which processes are

more important is given.
In this study, the same methodology is chosen for all of the 5 t-shirts. The results are based on the defined Goal and Scope, and they are aligned with the assumptions of the collected data and the chosen method.

The input data for all the 5 t-shirts are provided by the company. The data for the imaginary t-shirt (552b) is also collected from ID® IDENTITY. It is also modelled with the same structure as the other t-shirts. Therefore, the result of this t-shirt is comparable to the 4 other t-shirts.

DISCUSSION

This section present the discussion points of the results from the LCIA.

Comparing the t-shirts in terms of their environmental performance should be done carefully. The objective is not to evaluate which of the t-shirts is superior overall, but rather to compare different categories individually. This will allow conclusions for each t-shirt, and for the commissioner to make better and more informed decisions. As can be observed in Table 20, the t-shirts score differently in different impact categories. This is mainly due to the difference in fibre composition and washing cycles. The table shows a comparison of the two t-shirts with mixed fibre compositions (0300 and 0370) and comparisons between each of the three t-shirts of 100% cotton (0510, 0552 and 0552b).

Table 20: *The difference between different styles in percentage is indicated as a characterised result, at midpoint level for 18 impact categories.*

Impact category	Recycled poly-cotton vs Virgin poly-cotton difference (%)	Better Cotton vs Convention-al cotton difference (%)	Organic cotton vs Convention-al cotton difference (%)	Organic cotton vs Better Cotton difference (%)
Global Warming Potential	-12.78%	-1.55%	-40.27%	-39.33%
Stratospheric Ozone Depletion	-9.99%	-0.69%	-69.57%	-69.36%
Ionizing Radiation	-5.40%	-1.28%	-9.43%	-8.25%
Ozone Formation, Human Health	-2.39%	-0.67%	-4.93%	-4.28%
Fine Particulate Matter Formation	-7.01%	-1.66%	-29.00%	-27.81%
Ozone Formation, Terrestrial Ecosystems	-2.38%	-0.68%	-4.93%	-4.28%
Terrestrial Acidification	-3.33%	-1.06%	-38.33%	-37.67%
Freshwater Eutrophication	-0.14%	-0.04%	-93.38%	-93.38%
Marine Eutrophication	-0.09%	-0.03%	-91.26%	-91.26%
Terrestrial Ecotoxicity	-1.96%	-0.37%	-6.63%	-6.29%
Freshwater Ecotoxicity	-11.71%	-0.35%	-92.13%	-92.10%
Marine Ecotoxicity	-6.75%	-0.09%	-89.61%	-89.60%
Human Carcinogenic Toxicity	10.20%	-3.77%	77.90%	84.88%
Human Non-carcinogenic Toxicity	1.59%	0.07%	-115.26%	-115.25%
Land Use	-0.15%	-0.03%	20.36%	20.39%
Mineral Resource Scarcity	-31.96%	-4.48%	-74.83%	-73.65%
Fossil Resource Scarcity	-11.88%	-1.98%	-22.26%	-20.69%
Water Consumption	-2.84%	-14.29%	-5.95%	9.73%
Water Scarcity	-3.01%	-16.84%	-6.26%	12.73%

As can be seen in the table above, the organic cotton t-shirt performs better than its cotton counterparts in most impact categories, except when it comes to

Human Carcinogenic Toxicity and Land Use - and in the case of Better Cotton, also Water Consumption and Water Scarcity are affected. In the following, a deeper look into some of the categories will be found (the categories are chosen by the commissioner):

Global Warming and Fossil Fuels

Looking at Climate Impact (Global Warming Potential), the t-shirt 0552 (made from organic cotton) performs best among all 5 t-shirts with a total of 5.85 kg CO_2 eq. This is approximately 40% lower than the t-shirt made from conventional cotton (9.80 kg CO_2 eq) and the t-shirt made from BC cotton (9.65 kg CO_2 eq). This amount of CO_2 eq is very significant and it comes from the organic cotton production having a much lower intrinsic Climate Impact than the conventional and Better Cotton cultivation. Compared to the t-shirts with mixed fibres, the results are comparable to, but lower than, the 100% Better cotton and the conventional cotton t-shirts. This is despite the fact that the mixed fibre t-shirts have been assumed to last 200 washes in average, where the 100% cotton t-shirts are assumed to last 110 washes. Between the two mixed fibred t-shirts, the 0370 t-shirt performs around 13% better than the one with virgin polyester.

Comparing the results of Global Warming Potential to Fossil Fuel Scarcity is useful to test consistency in the results. We found that the pattern is similar between the two categories, indicating robustness in the pattern, since generally the Climate Impact is associated with the extraction of fossil fuels.
Comparing the two t-shirts with mixed fibres to each other, they show fairly similar results for most of the results. However, when it comes to Fossil Fuel Scarcity, there is a benefit of the recycled polyester of 12%.

Human Toxicity

Comparing the Better Cotton t-shirt to the conventional cotton one, it shows the benefit of 4% from the former to the Human Toxicity impact category. However, the difference between the environmental pressure arising from organic cotton and Better Cotton, organic cotton and conventional cotton, as well as recycled poly-cotton and virgin poly-cotton are noticeably high (≈ 85%, 78% and 10%, respectively). Looking at the results from weighting methods, these differences come from the production of different materials such as industrial fertilisers/pesticides for cotton production, the substances used for polyester fibre or/and the chemicals used in the dyeing process. As it is a consequential model, it is important to remember that also the indirect environmental impact of relevant processes are taken into account. For example, the initial source for the used heat in the washing process could have a damage on human health. Also, the results from the process of treating wastewater shows the water could be contaminated with metals or chemicals.

Land Use

Taking a closer look at the Land Use category, organic cotton performs worse than conventional cotton environmentally, due to the less intensive growing of cotton, which requires more land per 1 kg cotton output than when using conventional methods. This is not surprising and it is consistent with academic literature. Interestingly, the mixed fibre t-shirts (0300 and 0370) perform worse than the conventional cotton and the Better Cotton t-shirts in terms of the environment. The reason is that the majority of the Land Use impact for the t-shirts 0300, 0370, 0510 and 0552b derives from wood chips used for energy production in the washing process in the industrial laundry. This is also why the two mixed fibre t-shirts have identical results in this category, and the conventional and Better Cotton t-shirts are the same, too. The exception to this pattern is the organic cotton t-shirt where the highest environmental impact comes from cotton farming.

Looking at the results of the process contribution analysis shown in Table 21, almost 100% of the electricity is being produced using wood chips. It is, however, important to remember that the system under this study is modelled with a consequential approach. This means that although almost no industrial laundry in Denmark or the EU is using wood chips for electricity production, this is probably arising from the consequence of this choice on another decision. Considering the same electricity use but in an attributional modelling (Table 22), it can be seen that the ratio for producing electricity, between compost and wood chips is almost 50% 50%. These results are specifically attributed to the system under study regardless of the environmental impact of the choice on the whole world.

Table 21. *Process contributed to the production of electricity for the laundry service in Denmark - Consequential approach.*

No	Process	(%) - Electricity, medium voltage {DK}| market for | Conseq, U
	Total of all processes	100
	Remaining processes	0.05
1	Wood chips, wet, measured as dry mass {RoW}| hardwood forestry, birch, sustainable forest management | Conseq, U	38.39
2	Wood chips, wet, measured as dry mass {RoW}| softwood forestry, pine, sustainable forest management | Conseq, U	29.03
3	Wood chips, wet, measured as dry mass {RoW}| softwood forestry, spruce, sustainable forest management | Conseq, U	28.16
4	Wood chips, wet, measured as dry mass {RoW}| hardwood forestry, beech, sustainable forest management | Conseq, U	2.85
5	Wood chips, wet, measured as dry mass {RoW}| hardwood forestry, oak, sustainable forest management | Conseq, U	0.54
6	Wood chips, wet, measured as dry mass {SE}| hardwood forestry, birch, sustainable forest management | Conseq, U	0.27
7	Wood chips, wet, measured as dry mass {SE}| softwood forestry, pine, sustainable forest management | Conseq, U	0.21
8	Wood chips, wet, measured as dry mass {SE}| softwood forestry, spruce, sustainable forest management | Conseq, U	0.20
9	Wood chips, wet, measured as dry mass {DE}| hardwood forestry, beech, sustainable forest management | Conseq, U	0.14
10	Wood chips, wet, measured as dry mass {DE}| softwood forestry, spruce, sustainable forest management | Conseq, U	0.06
11	Wood chips, wet, measured as dry mass {DE}| softwood forestry, pine, sustainable forest management | Conseq, U	0.05
12	Wood chips, wet, measured as dry mass {CH}| hardwood forestry, mixed species, sustainable forest management | Conseq, U	0.03
13	Wood chips, wet, measured as dry mass {DE}| hardwood forestry, oak, sustainable forest management | Conseq, U	0.03
	Wood chips total	**99.95**

Table 22. *Process contributed to the production of electricity for the laundry service in Denmark - Attributional approach.*

No	Process	(%) - Electricity, medium voltage {DK}| market for | Conseq, U
	Total of all processes	100
	Remaining processes	2.13
1	Compost {RoW}| treatment of garden biowaste, home composting in heaps | APOS, U	50.89
2	Wood chips, wet, measured as dry mass {SE}| hardwood forestry, birch, sustainable forest management | APOS, U	13.13
3	Wood chips, wet, measured as dry mass {SE}| softwood forestry, pine, sustainable forest management | APOS, U	10.00
4	Wood chips, wet, measured as dry mass {SE}| softwood forestry, spruce, sustainable forest management | APOS, U	9.71
5	Wood chips, wet, measured as dry mass {DE}| hardwood forestry, beech, sustainable forest management | APOS, U	6.64
6	Wood chips, wet, measured as dry mass {DE}| softwood forestry, spruce, sustainable forest management | APOS, U	2.75
7	Wood chips, wet, measured as dry mass {DE}| softwood forestry, pine, sustainable forest management | APOS, U	2.28
8	Wood chips, wet, measured as dry mass {DE}| hardwood forestry, oak, sustainable forest management | APOS, U	1.26
9	Compost {FR}| treatment of garden biowaste, home composting in heaps | APOS, U	1.20
	Compost total	**52.09**
	Wood chips total	**45.77**

Water

When it comes to water, the study ‘A Comparative Study of Cotton Cultivation Practices in India’ investigating 10 farms, finds a lower water consumption for Better Cotton compared to both organic cotton and conventional cotton. The difference between water consumption and water scarcity is a multiplication factor that is set for each region according to how scarce the water of the region is. The cotton has been modelled to come from the same region (Bangladesh) and it is therefore not surprising that the water scarcity category result follows water consumption, when looking at either the cotton or mixed t-shirts. Comparing the mixed fibred t-shirts with the 100% cotton ones, the water scarcity is much higher for the 100% cotton t-shirts compared to the mixed. This is due to the fact that the areas in which cotton is farmed have higher water scarcity levels than the places where petroleum is extracted. The Better Cotton t-shirt is, however, comparable in this aspect to the two mixed fibre t-shirts. Note the difference between Water Consumption and the Water Scarcity. The Water Scarcity index gives a value of 1 to regions that have the same amount of water available as the world average. This means that in the case of the water consumption and the water scarcity having the same value, the consumption of water is taking place in places with average water availability. In contrast, when the water scarcity is higher than the water consumption, the water is being used in areas that have less available water than the world average. In the present case, there is higher than a factor 30 difference, indicating that the water consumption is taking place in areas with fairly high water stress (the scale of the index goes from 0.1 when water is plentiful to 100 when very scarce). Interestingly, the water stress level for Bangladesh, where the cotton is produced, has a fairly low water scarcity index (of 3) compared to the one for Europe (of 48.9) (Wulca, 2019).

The conventional cotton and BC cotton perform very similarly - only the water consumption and water scarcity differs significantly. In those two categories, BC cotton performs 14 and 17% better than conventional cotton for water consumption and water scarcity respectively.

Ecotoxicity

Taking a closer look at Marine and Freshwater Ecotoxicity, there is a clear pattern that the organic cotton t-shirt has a superior environmental impact. Compared to the two 100% cotton counterparts, the organic cotton t-shirt has around 90% environmental impact reduction in both of these impact categories. The reason for this is the pesticide and fertiliser use that is avoided in organic cultivation. Comparing Better Cotton to conventional, the differences are quite tiny in both those categories, which boils down to a similar pesticide and fertiliser use between the two. Comparing the recycled poly-cotton and virgin poly-cotton t-shirts, these also have very similar values. This is explained by looking at the process contribution, which shows that between 86% and 89% of the environmental burden comes from cotton farming in the Marine and Freshwater Ecotoxicity respectively.

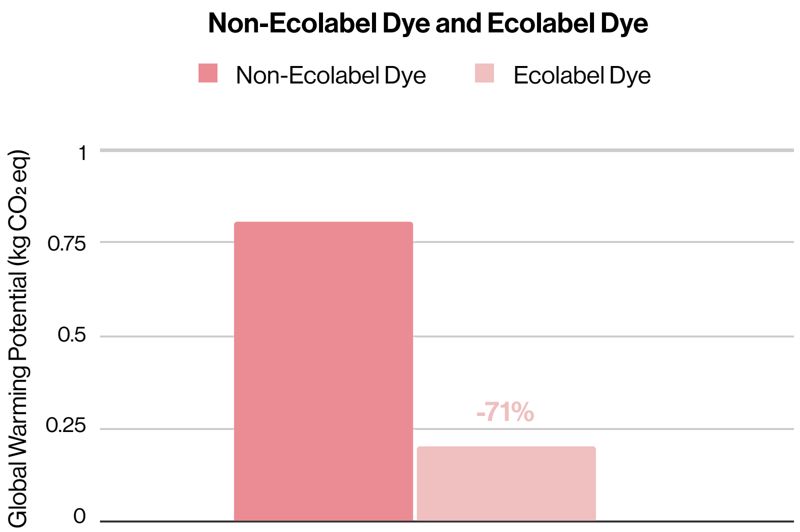

Figure 22. *The difference between style dyeing processes (%) is indicated as characterised result, at midpoint level for Global Warming Potential impact category (t-shirts 0300 & 0370)*

Interestingly, the chemicals deriving from dyeing processes do not result in high Toxicity impacts overall. This is due to the high quality dyeing processes in the facility used. The difference between the normal dyeing process and the Ecolabel dyeing process, however, is quite significant. The Ecolabel dyeing process shows an over 70% reduction in Global Warming Potential compared to the non-Ecolabel and a 26% reduction in Water Scarcity impact. These are significant reductions and depending on the impact category, the reduction in relation to the entire life cycle of the products, Mineral Resource Scarcity offers a 28% reduction and Human Carcinogenic Toxicity similarly offers 21%. For Global Warming Potential the reduction is 7% and for Fossil Resource Scarcity approximately 6%, Water Consumption drops by almost 3% from this change.

Comparing the two processes directly and comparing their isolated impacts, we see that the Ecolabel process results in dramatic reductions. See Figure 22 and 23 for comparison of Global Warming Potential and Water Scarcity impact.

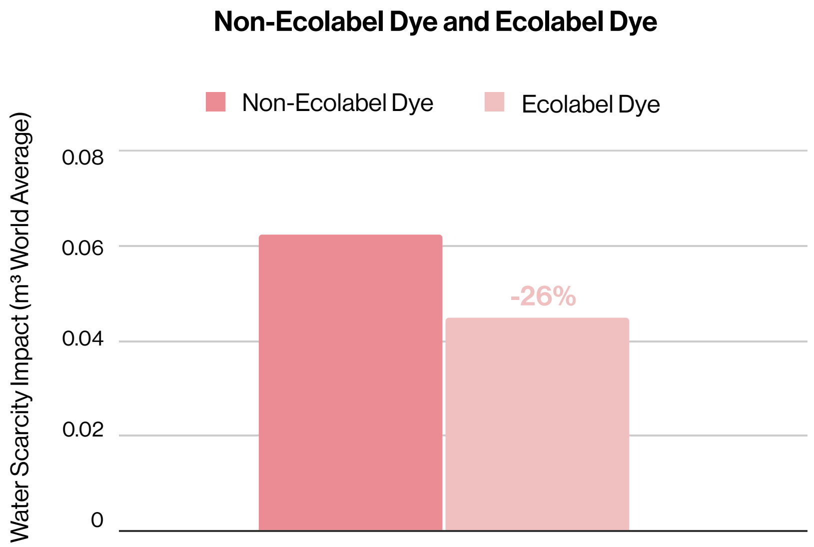

Figure 23. *The difference between style dyeing processes (%) is indicated as characterised result, at midpoint level for Water Scarcity impact category (t-shirts 0300 & 0370)*

The documentation from the commissioner comes in the form of test results of the waste water from the dyeing mill for every month of the year 2021. Comparing the wastewater test results to generic processes found in databases, the difference is very significant. It would therefore be likely that environmental studies done on textile productions using average dyeing mills would have quite significant Ecotoxicity impacts coming from the dyeing facility.

Terrestrial Ecotoxicity has a different pattern. The two t-shirts containing polyester need more natural gas for heating. These two, therefore, have a higher environmental impact in this category compared to the three t-shirts of 100% cotton.

Eutrophication

The two Eutrophication categories (Freshwater and Marine) both have the same pattern. The organic cotton t-shirt performs significantly better than its two cotton counterparts with more than 90% reduction in both Marine and Freshwater Eutrophication. This is explained by the fertiliser use that accounts for close to the entire environmental impact (between 91 and 93% depending on the t-shirt). That the cotton cultivation is that significant is also the explanation why there is almost no difference between the recycled polycotton and the virgin poly-cotton mixed t-shirt. The polyester, whether recycled or not, simply does not matter compared to the environmental burden of the cotton production. This is also the reason why the mixed fibres perform better than the conventional and Better Cotton t-shirts - they simply contain less cotton.

Life cycle stages

Dividing the environmental impacts into the different life cycle stages allows for a closer look into which areas in the supply chain that have the highest impacts. This is also called Hotspot analysis. The data in its entirety can be found in Appendix E for a closer look at the distribution of environmental impacts by t-shirt and impact category.

Figures 24 to 26 indicates the Hotspot analysis of t-shirt 0300 on 3 different impact categories in percentage, namely, Global Warming Potential, Freshwater Ecotoxicity and Freshwater Eutrophication.

It is important to note that the transportation is included in almost all stages (shown in Figures 3 to 7), however it is mentioned in the repacking stage specifically as this transportation refers to the longest trip and repacking has a very tiny involvement in the impact arising from this stage.

In the graph below a visual representation of the distribution between the different life cycle stages are shown for Global Warming Potential for t-shirt 0300. The use phase accounts for more than 50% of the total impact, followed by the fibre extraction phase, accounting for around 22%

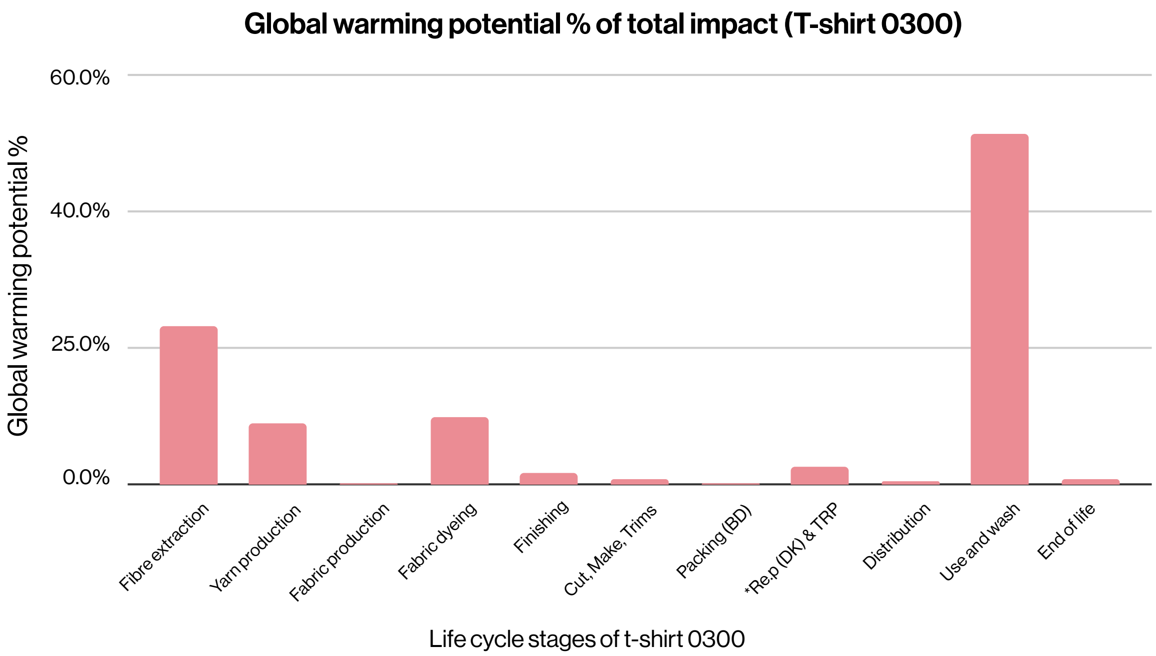

Figure 24. *The environmental burden of t-shirt 0300 on the Global Warming Potential category arising from each stage of its life cycle.*Re.p (DK) & TRP is an abbreviation for 'Repacking & transporting to DK'*

Compared to Water consumption, Water Scarcity takes into account where the water is taken from. Water taken from places with very little water available has a higher impact compared to water taken from areas with plenty of water. In the below graph the water scarcity impact for t-shirt 510 is presented. Highest impact of almost 50% is associated with the early stage of the production (fibre extraction) and the second highest is in the use stage where the final product is being washed (just about 40%).

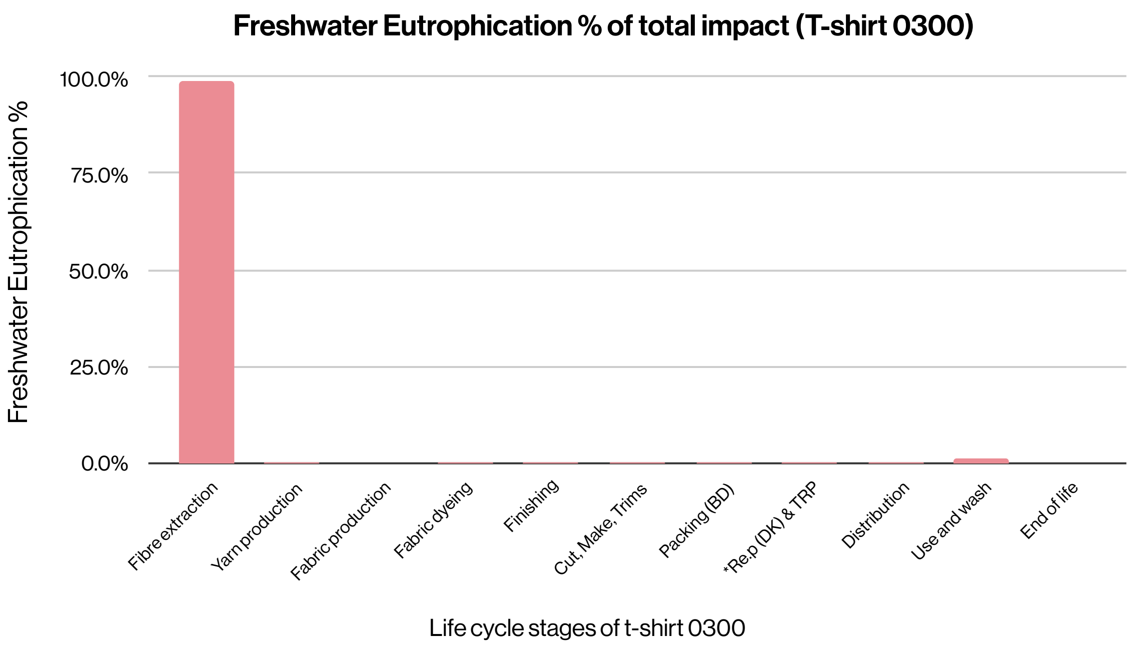

Figure 25. *The environmental burden of t-shirt 0300 on the Freshwater Eutrophication category arising from each stage of its life cycle.*Re.p (DK) & TRP is an abbreviation for 'Repacking & transporting to DK'*

Looking at Freshwater Eutrophication on the other hand, the pattern changes. As can be seen below, the vast majority of the impact comes from fibre extraction, which accounts for almost 100%. The second highest stage is the Use phase, accounting for about 1% of the total.

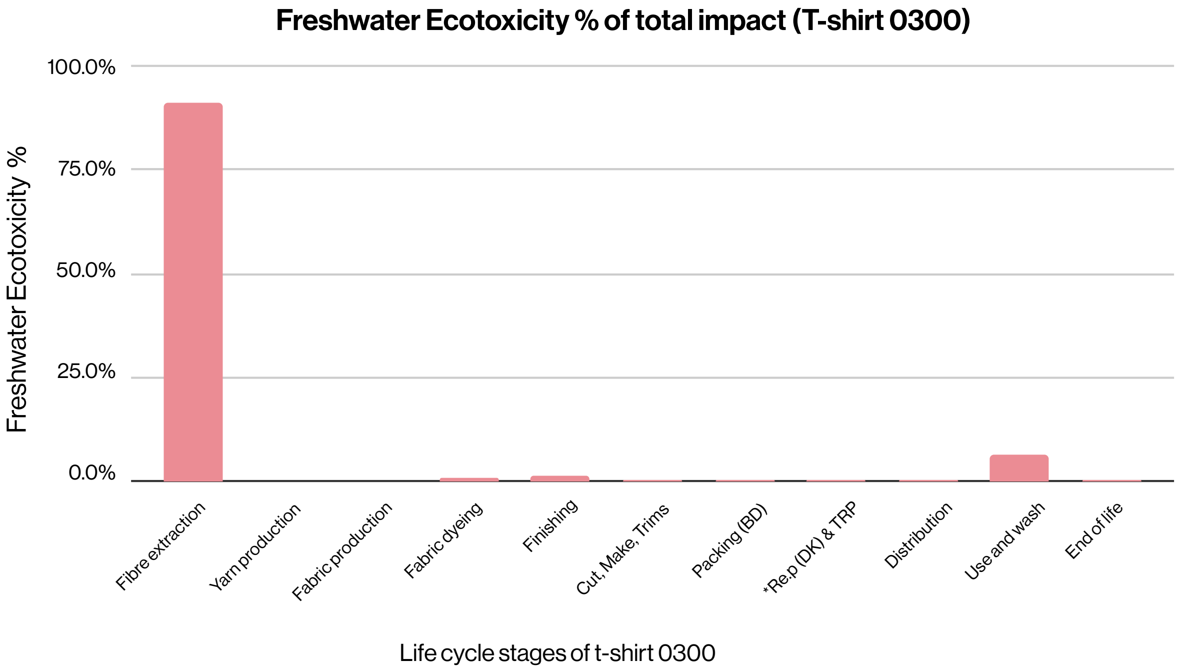

***Figure 26**. The environmental burden of t-shirt 0300 on the Freshwater Ecotoxicity category arising from each stage of its life cycle. *Re.p (DK) & TRP is an abbreviation for 'Repacking & transporting to DK'*

Similar pattern as Freshwater Eutrophication is mirroring the Freshwater Ecotoxicity (shown for t-shirt 0300). The highest impact is arising from the fibre extraction stage and the second highest is the Use phase (≈ 90% and ≈ 6%, respectively for freshwater ecotoxicity and ≈ 98% and ≈ 1% for freshwater eutrophication). Dyeing and finishing stages are accounting for less than 2%.

Normalised results

The normalised results are converted to measure how significant the impacts are in comparison to the impacts of an average global citizen. This provides insights into which categories are high or low and allows us a perspective on comparing the results across different impact categories.

The results as shown in Table 13 (Normalised results) show that Freshwater Eutrophication is among the highest of all the impact categories. Also in the high end, we find Marine Eutrophication and the two aquatic toxicity categories (Marine and Freshwater Ecotoxicity).

The importance of this can be underscored by Planetary Boundaries - an attempt by Stockholm Resilience Centre to quantify the planetary stability and the categories most significant for keeping our planet in a stable state. The Planetary Boundaries indicate the elements of eutrophication and ecotoxicity (in the Planetary Boundary framework called “Biogeochemical flows” and “novel entities” respectively) are one of the categories in the most dire state - the one threatening the planetary stability the most.

Weighted results

Weighted results are attempts to support decision makers by giving a weight to each impact based on a larger set of priorities and principles. As mentioned earlier, there are naturally various approaches to this.
The weighted results provide what is known as a single score - as well as scores for individual impacts. Looking at the two weighting methods, Environmental Prices and the Environmental Footprint approach, a similar pattern is found. The pattern gives an overall lower impact score to the t-shirt from organic cotton, followed by the t-shirts from mixed fibres and with the highest score, the conventional and Better Cotton t-shirts. In the Environmental Footprint method, the result is clearer but the pattern is the same for the two.

Given that these are different methods, there is a slight difference in the impact categories between them and the characterised and normalised results.

Land

We observe that the category “Agricultural Land Occupation” is a high contributor in all of the t-shirts when looking at Environmental Prices. Interestingly, the two t-shirts of mixed fibres have the highest impacts. Diving deeper into the process contribution, it is found that only about 4% of the agricultural land occupation impact of the 100% cotton t-shirts comes from the cotton fields. Instead, the impact largely is attributed to wood chips that come from forest management - used as fuel. As it turns out the polyester processing needs more of this to get the desired result.

Panning to the Environmental Footprint, there is no "Agricultural Land Occupation", but only a Land Use category which does not have a significant impact on the single score. The reason for the differences can be found in the different approaches to evaluating impacts.

Ecotoxicity

Terrestrial Ecotoxicity is also a high contributor when looking at the Environmental Prices. All the t-shirts have similar impacts in this category. The contribution to Terrestrial Ecotoxicity comes from the use of dehusked coconut for two different purposes in the industrial wash of the t-shirts: 1. To eventually produce the fatty acid needed for the liquid detergent and softener, and 2. To produce coconut oil that affects the soil and its surface when using pesticides (heavy metals), as well as soil cultivation.

Going back to the Environmental Footprint method, the Terrestrial Ecotoxicity does not seem to contribute high impacts to the Terrestrial Ecotoxicity. This also fits with the normalised results.

Eutrophication

Eutrophication however, is a category that both methodologies agree on being of importance. For Environmental Prices, especially the Marine Eutrophication is high where the Freshwater Eutrophication is higher in Environmental Footprint. This also fits with the normalised results.

Different approaches

A deep look into the methodologies,shows that they disagree on which of the impacts are more important and more significant. This is due to their different approaches to weighting the impact categories as explained in the section on weighting. However, what they do agree on, is the pattern of the organic t-shirt having a lower impact followed by the mixed fibres and the Better Cotton and conventional cotton t-shirts have the overall highest impacts (See section Weighting).

CONCLUSIONS

This section summarizes the results and discussion points.

The aim of this study was to understand the impacts of 5 t-shirts by ID® IDENTITY regarding a range of 18 environmental impact categories. This was done with the purpose to provide ID® IDENTITY with information that could be used to make decisions and to allow customers to take into account the environment into their purchasing decisions.

This LCA project should not be used for comparison with other product systems. Nor is the purpose of this study to decide which of the studied product systems is overall superior in terms of environmental impacts. Evaluating a large range of impact categories, this study is attempting to aid the commissioner in making decisions. Decisions on which product is preferable to another overall, however, is a normative choice that should be done by the receiver of the study. What this study can be used for is sharing insights about the different environmental performances the t-shirts have, where these impacts come from and recommendations for where to focus efforts in the future. This may guide the reader in making changes to their supply chain, business model or design processes.

The following section will present the conclusions and recommendations.

Fibres

The t-shirts investigated in this study all have different fibre compositions. It is not the aim of this study to point to one t-shirt or one fibre composition and deem it best or worst and the results don't support such an evaluation either.

Hotspots

The impact categories that keep on emerging in the analyses are the ones related to Ecotoxicity and Eutrophication. The impact comes primarily from the fibre production stages.

Land occupation seems to be very significant in the use and wash stage as well as in the fibre extraction stage. The reason for the use and wash stage contributing to the Land Use impact is the wood needed for creating heat for the drying process of the industrial laundry. This is by far the most important contributing factor. Second to the wood for heating is the cultivation of cotton that is needed for all five t-shirts. Here, the impact of organic cotton is significantly higher than the ones for conventional cotton and Better Cotton. The reason being that organic cotton has a lower output per hectare and thereby needs more land to produce the amount of cotton needed for the t-shirt. Between the Better Cotton and the conventional cotton, the values are almost identical. The fibre extraction stage for the t-shirts 300 and 370 are significantly lower than the three above mentioned t-shirts, which fits with the lower amount of cotton needed for the t-shirts since they are made from a poly-cotton mix.

Regarding the life cycle stages, the use phase has shown to be a very significant contributor to a range of impacts comprising for example around half the Global Warming Potential impact and between 45 and 70% of the water consumption depending on the t-shirt.

Dyeing has shown to be a less significant contributor to the Ecotoxicity impacts. The reason for this being that the production setup studied here, the dyeing process has a much cleaner use of chemicals leading to that the waste water not containing substances harmful to the environment. However, comparing the different dyeing methods (Ecolabel compliant and non-Ecolabel compliant) there is a large percentage difference between the two.

Transport has shown to be of little importance for the overall impacts. This aligns with other studies that consider non-air based transportation in a textile context.

Reducing impacts

The number of uses has a significant impact on the overall environmental pressure of the products. Driving up the number of times that the products are used, will lower the environmental impacts by up to 30% depending on the impact category.

Since quite a high fraction of impacts are found in the use phase, there might be opportunities for reducing these by engaging in dialogue with the industrial laundry facilities to reduce the amount of natural gas, electricity use and water consumption. Energy production has a big impact on the climate due to the burning of fossil fuels to create it. The reduction of 50% in greenhouse gas emissions by the supplier responsible for the knitting to packaging stage, planned for being implemented in 2030, will cause a reduction in Climate Impact of the total system of 8-16%.

A shift from conventional or Better Cotton to organic cotton will result in the reduction in several impact categories, while increasing especially Land Use. Compared to Better Cotton, a shift to organic cotton would cause an increase in Land Use (around 20%), Water Consumption (between 6% decrease to 10% increase) and in Water Scarcity (between 6% decrease to 12% increase). However, this shift would also come with significant reductions in a range of impacts, for example climate (around 40%) as well as Eutrophication and Ecotoxicity (around 90%).

TEKSTIL REVOLUTIONEN

RECOMMENDATIONS & FUTURE WORK

This section presents the recommendations for the next steps to be taken.

Below is a list of the most important recommendations based on the results of the report.

Engage with the laundries

- **Obtain information of reasons for end-of-life.** By getting more granular data and information on the ending of the service life of the products possibilities for improvement might emerge. This would include an in-depth analysis of the barriers to a longer lifespan. Whether the end of life is mainly due to the technical aspects, such as technologies related to spinning and knitting for example, or on the other hand has more to do with how the T-shirts are washed or used will be the foundation for possible actions to take. Way of doing this could be to take back used products to evaluate their state.
- **Motivate laundries to reduce resource use.** To lower the impact, it is recommended to reduce the consumption of water during washing, both by advancing and applying the most recent technologies but also by smarter use of existing facilities.
- **Engage in projects to extend service life.** By engaging in projects - for example behaviour change campaigns or improved design practices - to increase the lifetime of the products, ID would be able to reduce environmental pressures significantly.
- **Investigate the performance of recycled polyester**. The recycled polyester fibre has been assumed to have equal service life as its virgin counterpart. Engaging with laundries could test this assumption and contribute to evaluating the overall benefit of using the fibre. This is especially important in the light of the recycled polyester performing only around 0-5% better in most impact categories, although higher in fossil fuel scarcity (9%) and human carcinogenic toxicity (24%).
- **Investigate washing routines.** By investigating if there are differences in washing and drying routines based on the fibre composition would help qualify the results further. Since the use phase, and effectively the washing, is allocated a significant part of the Global Warming Potential, this might be a point to clarify further.

Engage with end-user

- **Get information about use.** To enable ID® IDENTITY to make better design and system decisions, it is recommended to engage with the end users regarding the number of washes, washing patterns, when a product ends its life because of aesthetic reasons and technical reasons.
- **Communicate about the impact of the end user.** Providing environmental information besides the washing guide on the t-shirts is recommended. This could be communication on how to prolong the use of t-shirts by following the care instructions. Another note could be including information on resource consumption and how much end users could save by increasing the lifetime.

Motivate suppliers

- **Support transition to renewable energy in the production stages.** The transition to renewable energy is important and has already started. By supporting, sharing and motivating suppliers, there is a chance of speeding up the process and broadening the transition out to more suppliers.
- **Holistic approach in the supply chain.** There are already efforts in the supply chain to cut down on the Climate Impact, which is of great importance. Signalling to suppliers that ID® IDENTITY is also concerned about other impact categories might help push attention to a more holistic approach, and thereby potentially avoiding problem shuffling.

Connect with farm level

- **More data on farm-level.** The farm level has shown to be very significant in important impact categories in this study. It is therefore recommended that the commissioner takes action to granular data on this stage. This would include the quantification of water-, pesticide and fertiliser use as well as output per hectare.
- **Investigate regenerative agriculture.** Regenerative agriculture can serve as a carbon sink, taking CO2 from the atmosphere and binding it in the soil. Trace the supply chain. Coming EU legislation will demand high levels of traceability in supply chains. Starting the journey before the mass market will give ID a competitive advantage and allow them to do the work in a thorough and diligent manner.

Material & design

- **Evaluate if dyeing can be omitted.** In some cases, dyeing accounts for 8% of the Climate Impact of the whole system. Eliminating this stage might be an option for some markets.
- **Push forward Ecolabel dyeing.** The Ecolabel dying process has huge potential for savings both on climate impact and water related impacts

Engage in recycling efforts

- **Look into alternative end-of-life.** The present study has modelled that the products become incinerated after the last use. To create a system where the products get a second life in the form of another product, this has a potential to reduce the environmental impact of the products.

As recommended, to lower the environmental impact of ID® IDENTITY's t-shirts, future investigation on new materials for t-shirt production and new ways to treat the waste is needed.

Regarding the materials, taking other alternative materials into consideration could be a great investment. In the case of t-shirts style 03, for instance, there are no considerable differences between the contribution of impact from 0300 and 0370 to the environment. Yet, some analysis such as the impact of microplastic is not considered in this study and it is known that materials made of plastic such as polyester, releases microplastics. Therefore, investigation on alternatives for polyester is crucial. Substitution for polyester should have the potential to increase the longevity of fabric, as well as reduce the environmental impact.

T-shirt 552 which contains 100% organic cotton could be investigated to be obtained from regenerative cotton. Regarding the waste treatment, ID® IDENTITY is considering collaboration with a recycler to ensure the best possible End-of-Life for their products. Although End-of-Life only accounts for less than 1% of Global Warming Potential, there might be potential to use the material for new products and thereby receiving "credits" for it.

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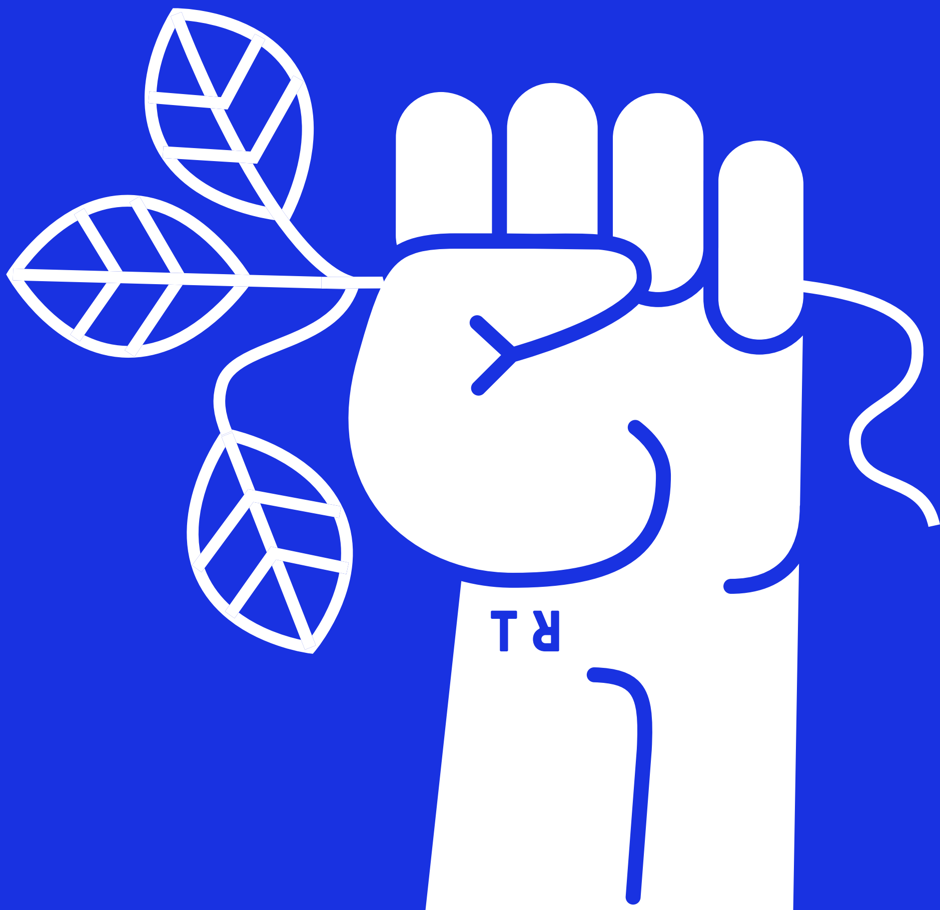

Critical review statement

SHALL BE PART OF THE REPORT

A concurrent critical review has been performed on “Life cycle assessment of 5 t-shirts” conducted by The Textile Revolution (Tekstilrevolutionen) (dated February 2023) and commissioned by ID Identity, by Kim Christiansen, kimconsult.dk, as an independent external reviewer. Requirements and recommendations from DS/EN ISO 14044:2008 and DS/CEN ISO/TS 14071:2016 have been used. The general requirements are covered by clause 6.2 of ISO 14044 and clause 4.3.4 on concurrent critical review and clause 4.5 on report and statement of ISO 14071.

The critical review report was done concurrently and iterative with the study and it was decided not to make it publicly available and therefore not to include it in the LCA study report.

The review included an assessment of the LCI model developed in SimaPro version 9.4.0.2 (2021) and company specific data as well as generic data from ecoinvent version 3.6 (2019) during workshops held at the premises of The Textile Revolution. Individual datasets have also been evaluated based on the outcome of contribution analyses and Monte Carlo simulations. Comments were delivered and resolved concurrently with the study by the reviewer. Input was also solicited from an external expert on consequential LCA after finishing the concurrent review. Comments were addressed as far as possible taking into account that the study is based on unit process data alone and does not include input/output (top-down) data.

I can hereby declare that

- the methods used to carry out the LCA are consistent with ISO 14044 and 14071,
- the methods used to carry out the LCA are scientifically and technically valid,
- the data use are appropriate and reasonable in relation to the goal of the study,
- the interpretations reflect the limitations identified and the goal of the study, and
- the study report is transparent and consistent.

Søborg, 2023-03-13