LIFE CYCLE ANALYSIS OF A SUPIMA COTTON T- SHIRT

COMPARISON BETWEEN A MADE-TO-ORDER AND A MASS PRODUCTION BUSINESS MODEL

March 2023

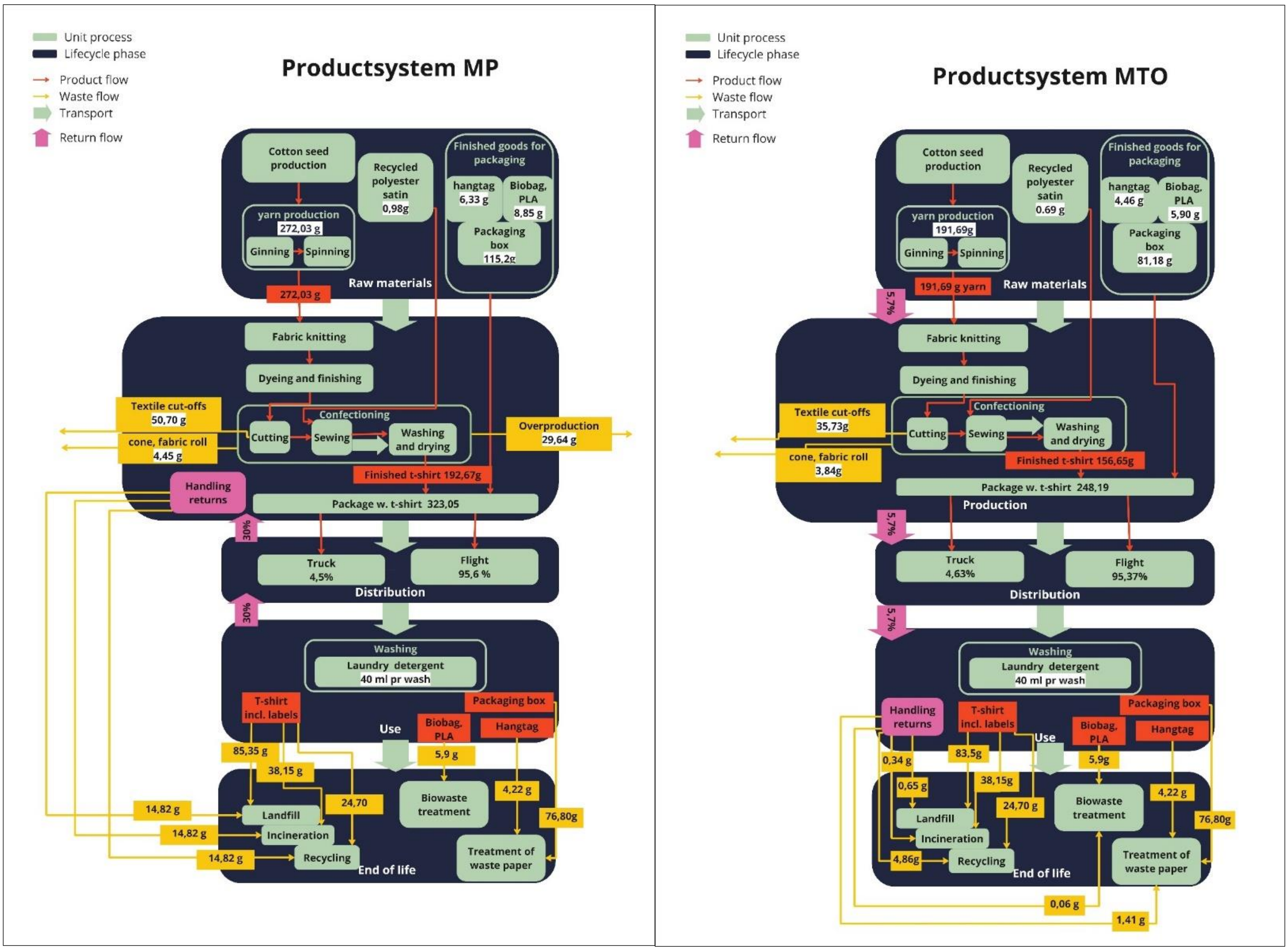
SUMMARY

Son of a Tailor is a clothing–technology company based in Copenhagen, Denmark. They make custom fit clothing for men, e.g., T–shirts, knitwear, activewear and more. Their vision for a different, more sustainable clothing industry is at the heart of everything they do, and they see it as part of their purpose to drive change on an industry level. Son of a Tailor's answer to this is as simple as it is radical: they only make what customers have ordered uniquely fitted to each customer's body. This way, they fight overproduction of clothing while delivering perfect fit for the customers. The production model that they use is called Made–to–Order.

The goal of this LCA is to compare the footprint of one Son of a Tailor Supima cotton T–shirt in two different production models. The models examined are Son of a Tailor's custom fitted Made–to–Order model and a Mass Production model based on Made–to–stock where deadstock of unsold products is unavoidable. To achieve this an LCA based on ISO 14040 and 14044 has been conducted from raw materials extraction to end–of–life (cradle–to–grave). The study assesses these two product systems in four different environmental impact categories:

- Global Warming Potential (kg CO_2e)
- Water Scarcity (m^3)
- Freshwater Ecotoxicity (1,4 kg DCB)
- Land Use (m^2)

The product systems for the two examined scenarios are shown in the picture below.



Data has been collected in collaboration with Son of a Tailor and their production suppliers in Portugal to obtain as much primary data as possible. The report and LCA has been conducted in the period 01.12.2022 – 31.03.2023.

Where primary data was not available due to lack of supplier transparency and low data availability, generic data as well as secondary data from the Ecoinvent 3.8 database was used. For the use phase and the end–of–life phase, literature has been studied to model those as precisely as possible, mapping out the waste treatment scenarios for the T–shirt and how a T–shirt is washed in its use phase. The data quality of the geographical representation is generally high, especially in tier 1, and as well as their customers market share. Data on transport distances between tier 2 suppliers has not been possible to obtain and so the representation in that regard is low. However, processes from Ecoinvent have been chosen and modified to best match the representative of the geographical representation. Since good data have been collected and provided by Son of a Tailor's production facility, it was possible to match the technological representation on a high level. Since the data used are of the newest available it can be assessed that the time representation is on a high level. Data in the use phase and end–of–life as well, has been selected to be as new as possible with most data in these phases being within five years. Data from tier 2 has been difficult to obtain, which is evident from the assumptions made in this LCA study. Son of a Tailor have had good communication with the fabric knitting facilities as well as their own production in Portugal, and so an adequate amount of specific data for the different processes in the production could be obtained. For the background activities, which is where Son of a Tailor does not have any operational and financial control, processes based on secondary data sets from the Ecoinvent database 3.8 have been used. These processes have then been modified to match Son of a Tailor's production and product. The applied processes are cut–off processes, meaning they use economic allocation.

During the LCA study, all primary data has been gathered with the support of the LCA consultants with weekly data collection meetings. During the data collection meetings, all data was double checked with Son of a Tailor to ensure the use of correct data sources. Both the collected data and the input data to the LCA are accessible and transparent. Raw data from the data collection of Son of a Tailor and input data for the LCA Study can be found in Appendix 2 and 5.

All data used for this study has been methodically reviewed for aspects pertaining to technology, time, and geography, following the guidelines of ISO 14044. In Appendix 3, a list of collected generic data, as well as quality evaluation for each of these aspects, can be found. The processes chosen in Ecoinvent 3.8 have also been evaluated and classified for each of these aspects. This can also be found in Appendix 3. The data Son of a Tailor has collected from their suppliers has been assessed as true and the best quality available.

LCA study shows that the Made–to–Order model generally has a lower impact in all impact categories, due to less deadstock and lower return rates; 29,66% lower in Global Warming Potential, 30,01 % lower in Water Scarcity, 33,97% lower in Freshwater Ecotoxicity and 40,36% lower in Land Use in a cradle–to–grave perspective. This shows a significant difference between the two business models, and how the Made–to–Order business model is generally better for the environment than the Mass Production business model in the case of Son of a Tailors production. The most contributing phase in all impact categories is the raw materials phase, where cotton seed is grown, harvested, and eventually ginned and pressed. In this phase the harvesting and growing of seeds pollutes the most. In the Global Warming Potential impact category, the distribution, transportation to distribution center as well as the dyeing and finishing of fabric in the knitting phase also has considerable influence. This is due to the T–shirts being transported mostly by airplane, as well as due to the use of natural gas in the dyeing and finishing phase. The use phase is the second largest contributor in Water Scarcity and Freshwater Ecotoxicity impact categories, mainly due to the water and electricity used during the lifespan of the T–shirt. This phase is also the most sensitive one since it is generally considered hard to model the use phase for products, due to general low data availability on how the users are washing and wearing their T–shirts. The study finds that the confectioning phase, where the T–shirt is being cut to size, sewed, ironed, and packed, has a general low impact compared to the other phases.

In conclusion, the Made–to–Order business model does have a positive impact on the T–shirt's environmental impact since deadstock is prevented and return rates are lower due to the custom fits. If Son of a Tailor were to improve their environmental footprint based on the results of this study, it could be done by using other transportation forms than airplane in the upstream and downstream transportation phases, as well as lowering the use of natural gas in the dyeing and finishing process. One way to lower the impact in the dyeing and finishing phase would be to substitute the natural gas consumption with another energy source that is less polluting.

The LCA study has been subjected to a third–party critical review. The critical review has been performed by Freja Jeppesen and Jonas Eliassen from the company 2.0 LCA Consultants. 2.0 LCA

Consultant have more than 20 years of experience working with LCA in a range of fields, including the textile industry. Their level of expertise is thus exceptionally high.

ABSTRACT

Son of a Tailor is a clothing–technology company based in Copenhagen, Denmark. They make custom fit clothing for men, e.g., T–shirts, knitwear, activewear and more. Their vision for a different, more sustainable clothing industry is at the heart of everything they do, and they see it as part of their purpose to drive change on an industry level. Son of a Tailor's answer to this is as simple as it is radical: they only make what customers have ordered uniquely fitted to each customer's body. This way, they fight overproduction of clothing while delivering perfect fit for the customers. The production model that they use is called Made–to–Order.

The goal of this LCA is to compare the footprint of one Son of a Tailor Supima cotton T–shirt in two different production models. The models examined are Son of a Tailor's custom fitted Made–to–Order model and a Mass Production model based on Made–to–stock where deadstock of unsold products is unavoidable. To achieve this an LCA based on ISO 14040 and 14044 has been conducted from raw materials extraction to end–of–life (cradle–to–grave). The study assesses these two product systems in four different environmental impact categories:

- Global Warming Potential (kg CO_2e)
- Water Scarcity (m^3)
- Freshwater Ecotoxicity (1,4 kg DCB)
- Land Use (m^2)

The data has been collected in collaboration with Son of a Tailor and their production suppliers in Portugal to obtain as much primary data as possible. Where primary data was not available due to lack of supplier transparency and low data availability, generic data as well as secondary data from the Ecoinvent 3.8 database was used. For the use phase and the end–of–life phase, literature has been studied to model those as precisely as possible, mapping out the waste treatment scenarios for the T–shirt and how a T–shirt is washed in its use phase.

The LCA study demonstrates that the Made–to–Order model generally results in lower impacts across various impact categories due to reduced deadstock and lower return rates. Specifically, when compared to a Mass Production model, The Made–to–Order model shows a reduction of 22,88% in Global Warming Potential, 23,08% in Water Scarcity, 25,36% in Freshwater Ecotoxicity, and 28,75% in Land Use when considering the entire product lifecycle. Conversely, if Son of a Tailor were to adopt a Mass Production business model, their environmental impacts would be significantly higher. In relation to the Made–to–Order model, the Mass production model would result in an increase of 29,66% in Global Warming potential, 30,01% in Water Scarcity, 33,97% in Freshwater Ecotoxicity, and 40,36% in Land Use.

This shows a significant difference between the two business models, and how the Made–to–Order business model is generally better for the environment than the Mass Production business model. The most contributing phase in all impact categories is the raw materials phase, where cotton seed is grown, harvested, and eventually ginned and pressed. In this phase the harvesting and growing of seeds pollutes the most. In the Global Warming Potential impact category, the distribution, transportation to distribution center as well as the dyeing and finishing of fabric in the knitting phase also has considerable influence. This is due to the T–shirts being transported mostly by airplane, as

well as due to the use of natural gas in the dyeing and finishing phase. The use phase is the second largest contributor in Water Scarcity and Freshwater Ecotoxicity impact categories, mainly due to the water and electricity used during the lifespan of the T–shirt. This phase is also the most sensitive one since it is generally considered hard to model the use phase for products, due to general low data availability on how the users are washing and wearing their T–shirts. The study finds that the confectioning phase, where the T–shirt is being cut to size, sewed, ironed, and packed, has a general low impact compared to the other phases.

In conclusion, the Made–to–Order business model does have a positive impact on the T–shirt's environmental impact since deadstock is prevented and return rates are lower due to the custom fits. If Son of a Tailor were to improve their environmental footprint based on the results of this study, it could be by using other transportation forms than airplane in the upstream and downstream transportation phases, as well as lowering the use of natural gas in the dyeing and finishing process. One way to lower the impact in the dyeing and finishing phase would be to substitute the natural gas consumption with another energy source that is less polluting.

CONTENT

1 GENERAL

This LCA study has been conducted according to the requirements in DS/EN ISO 14044:2006

1.1 COMMISSIONER

Tailor shaped Aps – Son of a Tailor
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CVR: 34732590

1.2 LCA PRACTITIONER

Transition ApS
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1550 København V

Att: Lasse Langstrup
Annika Nørgaard Karmann
Astrid Yde Larsen

1.3 CRITICAL REVIEW

2.-0 LCA consultants
Rendsburggade 14
9000 Aalborg

1.4 DATE

This report is conducted in the period 01.12.2022 – 31.03.2023.

1.5 GLOSSARY

Made-to-Order:
A Made-to-Order business model means that the production is first initialized when an order from a customer has been made. In this report Made-to-Order is abbreviated as MTO.

Mass Production:
A Mass Production business model means that there is a continuous stream of production based on a sales forecast. In this report Mass Production is abbreviated as MP.

Deadstock:
Deadstock fabrics are the "leftovers" of apparel production. These are fabrics and products that either ended up not going to the intended buyer at all after being produced, or that have not been made into finished garments.

Return rates:
A return rate is the average annual rate of returned garments and apparels from customers or retail stores.

Waste fabric:
Waste fabric is produced under the production phase confectioning, where the fabric is cut and sewn into the intended form.

1.6 NOTE ON DECIMAL NOTATION

This LCA has been modelled using SimaPro and the Ecoinvent 3.8 database according to Danish standards. This means that the decimal notation of graphs, percentages and other results takes form of a comma (,) and not an English decimal point (.), since this is the national standard.

2 BACKGROUND AND OBJECTIVES

2.1 BACKGROUND

Son of a Tailor is a clothing–technology company based in Copenhagen, Denmark. They make custom fit clothing for men such as T–shirts, knitwear, activewear and more. They are on a mission to re–engineer the clothing industry for the planet and people. As for many entrepreneurial endeavors, the idea for Son of a Tailor was born out of frustration. Once celebrated as one of the biggest achievements in manufacturing, mass production failed the planet and people alike through creating mountains of unsold clothing that end up in landfills or burned, and through clothing that fits here but not there and thus ends up being returned or thrown out.
Son of a Tailor's answer is as simple as it is radical: they only make what customers have ordered, uniquely fitted to each customer's body. This way, they fight overproduction for the planet while delivering perfect fit for the customers.
Their vision for a different, more sustainable clothing industry is at the heart of everything they do, and they see it as part of their purpose to drive change on an industry level. They hope that the Son of a Tailor business model can inspire other companies to adopt similar demand–driven supply chains. This ambition is based on the strong belief that their Made–to–Order model has a significantly lower environmental impact.

The main goal of this Life Cycle Assessment is to gain further insight into the impact of their business model and to have third–party verified proof that it is indeed preferable to Mass Production from an environmental point of view. To achieve this, a comparative scenario is established for comparison with Son of a Tailor's business model. The comparative scenario is built upon the three main principles of Mass Production (Hollstein & Tannenbaum, 2023):

1. Division of total production operation into specialized tasks.
2. Simplification and standardization of component parts to permit large production runs.
3. Development and use of specialized machines, materials, and processes.

Son of a Tailor's production model differs from the Mass Production model on point number two. Due to their on–demand production and unique fit, their products are not standardized, and therefore cannot be pre–produced in large quantities. Following this it is assumed that a normal Mass Production business model would be using a so–called Made–to–stock business model, meaning that products are standardized, and production is based on sales forecasts. On this basis, the Made–to–stock model has been chosen to represent a Mass Production business model to be compared with Son of a Tailor's Made–to–Order business model.
For the duration of this report, we will refer to the Mass Production model as MP and Made–to–Order model as MTO.

The comparison will be based on the production of one of Son of a Tailor's basic cotton T–shirts. The T–shirt is made of Supima cotton, a material chosen for its high quality. This type of cotton has extra–long staple, which makes the cotton stronger and more resistant to pilling, breaking, and tearing, ensuring a longer lifespan (Supima, 2023).

The study aims to deliver the necessary information through an LCA based on the requirements in DS/EN ISO 14044:2006. It is in Son of a Tailor's interest to communicate the results of this report both internally and externally. For further explanation of the methodology and the LCA study limitations, see section *3.2 Lifecycle methodology* and *3.3. Cut–off criteria for initial inclusion of inputs and output.*

2.2 GOAL AND OBJECTIVES

This chapter will describe the goal and objective of the study. Additionally, it will shortly introduce which two systems the LCA study aims to compare. The goal phase of an LCA describes what the purpose and objectives of the LCA are to ensure that the reader knows why the LCA is performed.

The goal of this study is to conduct a life cycle assessment of 1 Son of a Tailor Cotton T–shirt in 100% extra–long staple Supima cotton, medium weight (150g/m2) in their MTO business model compared to a MP business model including deadstock and return rates. Further, the goal is also to know the baseline impact of 1 Son of a Tailor Cotton T–shirt in 100% extra–long staple Supima cotton in a cradle–to–grave perspective.

The main objectives of the study are:

1) To compare the environmental performance of Son of a Tailor's MTO business model with a MP business model.
2) To calculate a baseline for Son of a Tailor's cotton T–shirt in Supima cotton from cradle–to–grave.

2.2.1 Function of the two compared models

Two different business models are compared:

Business model 1: Made–to–Order (MTO)
The T–shirt is produced in Son of a Tailor's MTO business model, meaning production is first initialized when an order has been made from a customer. This includes the waste fabric in the production and return rates of the T–shirt.

Business model 2: Mass Production (MP)
The T–shirt is produced in the MP business model, meaning there is a continuous stream of production based on a sales forecast. This includes the waste fabric in the production, deadstock of premade fabric not being sold, and return rates of the T–shirt.

These models will be elaborated throughout the life cycle inventory. The comparison cannot make any assessments on what the best approach for an apparel business model is. This means that the comparison is specifically focused on the different business models and their effects on the environmental impact of a T–shirt using the same data provided by Son of a Tailor's production facilities.

2.3 USE OF THE STUDY AND TARGET AUDIENCE

The comparative results of this study are intended to be used by the commissioner, Son of a Tailor. The LCA study is intended to be used for external communication to Son of a Tailor's customers, e.g. retail customers, for informational purposes. Therefore, a critical review is necessary to allow the LCA study and its results to be disclosed. According to the ISO standards on ISO 14040 and 14044:2006, this requires a critical review process undertaken by a third–party critical reviewer.

2.3.1 Critical review

The LCA study has been subjected to a third–party critical review. The critical review has been performed by Freja Jeppesen and Jonas Eliassen from the company 2.0 LCA Consultants. 2.0 LCA Consultant have more than 20 years of experience working with LCA in a range of fields, including the textile industry. Their level of expertise is thus exceptionally high.

3 SCOPE

In this chapter the scope of this LCA study will be defined through the introduction of the functional unit as well as the system boundaries, methodology and cut–off criteria. The scope phase of an LCA essentially defines what is included and excluded in the study.

This LCA study is intended for external communication, and therefore the report requires inclusion of all phases of an LCA as well as a third–party critical review. A third–party report is also conducted. By the ISO 14044 guidelines, this must be publicly available to any external party to read if they desire. The third–party report is a separate document.

3.1 FUNCTION AND FUNCTIONAL UNIT

The function examined in this LCA study is the production of one Cotton T–shirt from Son of a Tailor including packaging. Two types of business models will be examined: Made–to–Order (MTO) and Mass Production (MP). The T–shirt comes in two weights, medium– and heavy–weight. The calculations in this report will focus on the medium–weight fabric, which means a density of 150 g/m^2. For the function and reference flow, see table 3.1.

According to the lifespan of the Supima cotton T– shirt, this LCA study will be based on an estimated average of 26 washes, which is 50% more than the average T–shirt (Daystar et al., 2019). This is based on research and test results which Son of a Tailor conducted with the Danish Technological Institute. Read more about the lifespan under the life cycle inventory, 4.9.1, and in Appendix 1.

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Function	Functional Unit	Reference Flow (RF)
A lifespan of 26 washes, equal to 50% more than the average T–shirt.	1 Supima Cotton T–shirt with a density of 150g/m^2, including packaging, care label, neck label and hang tag, for a lifetime of 26 washes.	1 Supima cotton T–shirt with density 150g/m2 including packaging, care label, neck label, and hangtag.

Table 3.1: Definition of the functional unit

3.2 SYSTEM BOUNDARIES

In this LCA, the full lifespan of a Supima cotton T–shirt produced by Son of a Tailor will be examined from cradle–to–grave. An overview of the system boundaries of the modelled processes can be seen in figure 3.1. The system boundaries determine which unit processes shall be included within the LCA. The selection of the system boundaries shall be consistent with the goal of the study. The criteria used in establishing the system boundaries shall be identified and explained. The system boundaries for this study includes the extraction of raw materials, transportation to production, production of the T–shirt, distribution to customers, use, and end–of–life. The quantification of energy and material inputs and outputs has been based on data collection from Son of a Tailor. Relevant calculations for the quantification of energy and material inputs and outputs will be shown throughout the inventory.

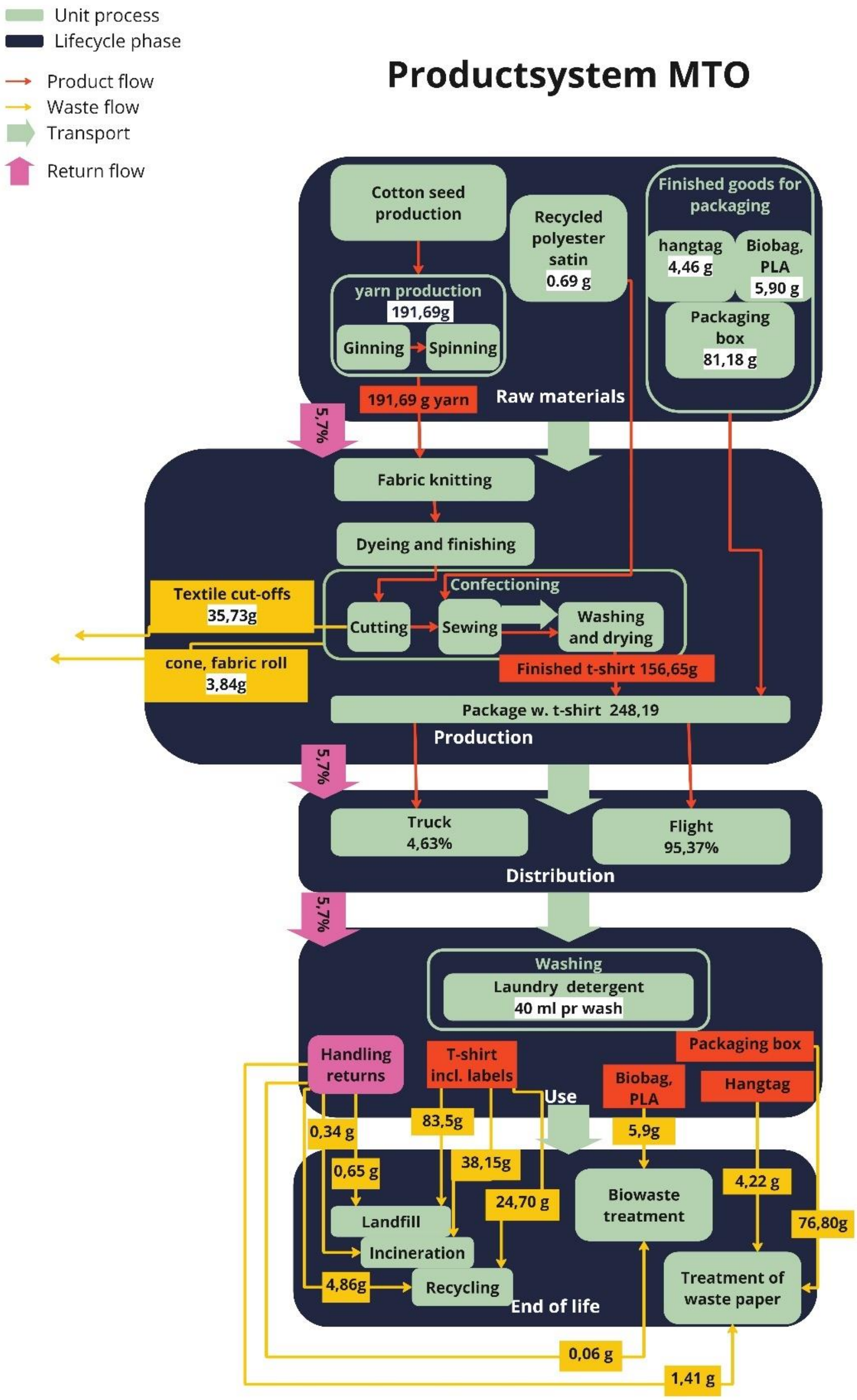

Figure 3.1: System boundaries MTO

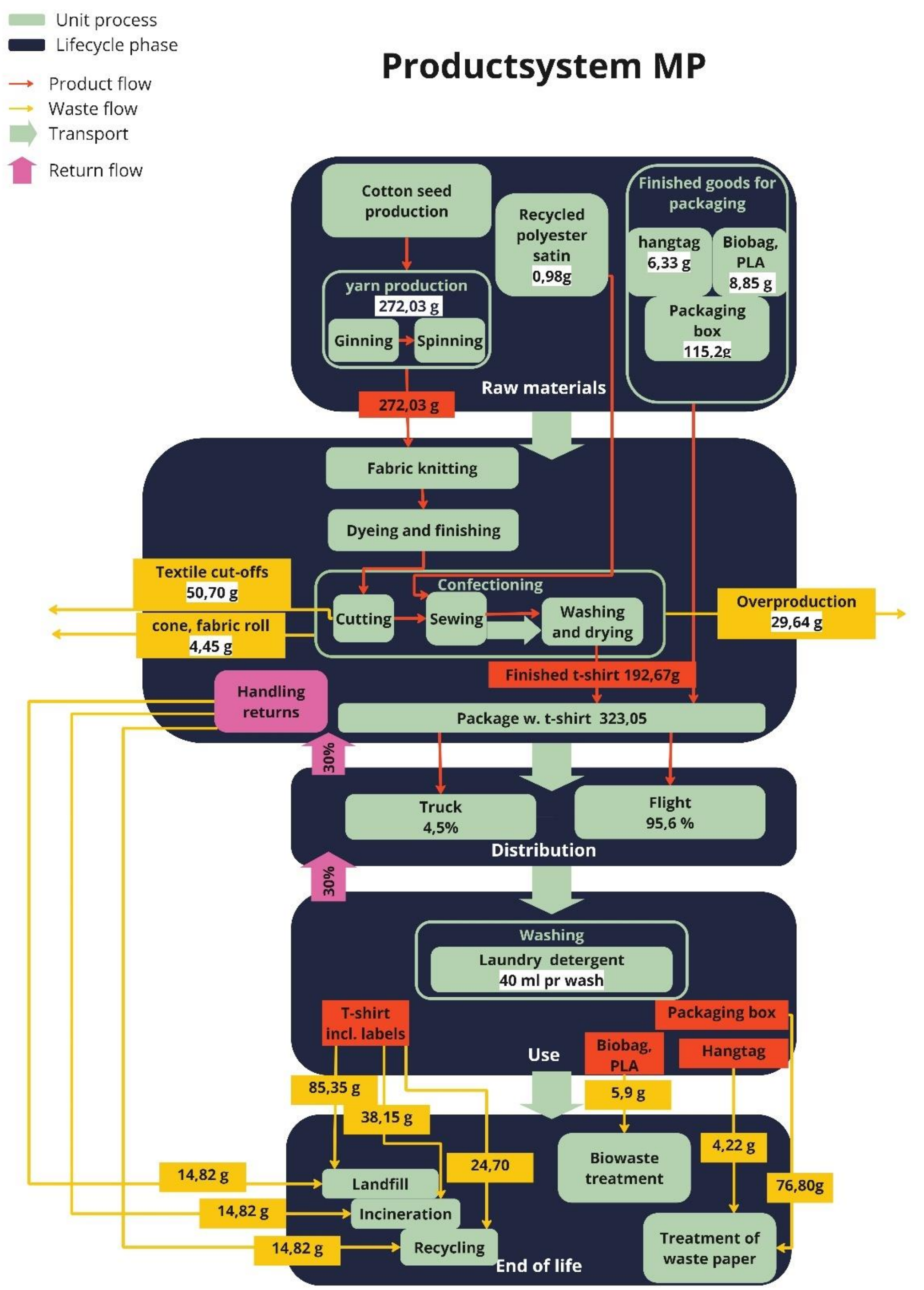

Figure 3.2: Product system MP incl. overproduction and returns.

Figures 3.1 and 3.2 illustrate the product systems associated with the MTO system and the MP system, respectively. Within the MTO, the product flow represents the entire lifespan of a T–shirt including returned items. The pink arrows depict the flow of returns after production. In the MTO system, returned items are handled by the customer and ultimately enter residual waste streams.

In contrast, the product flow in the MP system reflects the lifespan of a T–shirt including both overproduction and returned items. Overproduced items are sent to waste handling in the production phase, whereas the returned items are assumed to be sent back to the production phase and thereafter put into waste streams.

Exactly how the systems differ will be explained further in section 4.2. (Differentiation of the two business models), as well as throughout the inventory.

It is important to notice that the product systems in figure 3.1 and figure 3.2 are simplified and do not represent the full inventory, but rather the overall product flow, to show the difference between the two examined business models. The most significant differences between the MTO and MP systems are that the MP system has overproduction, and that the return rates and handling of returns is different between the two systems. This difference will be elaborated further in section 4.2.

The difference in handling returned items is also why it is important to include the end–of–life phase of the product.

To clarify for the reader of this report, the end–of–life phase has been split into three different phases in the assessment and can be identified as:

- End–of–life of used T–shirt
- End–of–life of returned T–shirt
- End–of–life of deadstock

End–of–life of used T–shirt is the same for both the MTO and the MP system since one T–shirt is used in both systems. The end–of–life of returned T–shirts differ in the MTO and the MP, which will be described in section 4.2. The end–of–life of deadstock only applies to the MP system since there is no deadstock waste in the MTO model due to the nature of the business model.

3.2.1 Life cycle methodology

The LCA study will be assessed in four selected impact categories. Category indicators and characterization models used are determined by the demands stated in ISO 14040/44 and chosen to give the best answers of the goal and scope. The impact categories were chosen in collaboration with Son of a Tailor based on their importance to what they want to communicate as well as their relevance to the type of product examined in the LCA. See table 3.2.

Impact category	Unit for result	Reference for characterization method
Global Warming Potential	kg CO2 equivalents	IPCC (2021) GWP100 as implemented in Simapro.
Freshwater Ecotoxicity	Comparative toxic unit for (1,4 DCB kg)	ReCiPe midpoint H (2016) as implemented in Simapro.
Water Scarcity	m^3 world equivalents	Berger et al. (2014) as implemented in Simapro
Land Use	m^2 crop equivalents	ReCiPe midpoint H (2016) as implemented in Simapro.

Table 3.2: List of chosen impact categories for LCA study.

Global Warming Potential is deemed an important factor due to the high focus on the matter in organizations, society, and politics, and given the evidence of climate change and increasing temperature of the planet. Freshwater Ecotoxicity is important due to chemical use in various processes when producing T–shirts. Water Scarcity is important since cotton farming and harvesting is known to use large amounts of water. Since the use phase includes the washing of the T–shirt, water use and thereby Water Scarcity is also relevant here. Land Use is also important since cotton farming and harvesting requires use of land for agricultural purposes. The chosen impact categories are also important and relevant in relation to the specific product of a T–shirt. From the current guidelines of the PEFCR for Apparel & Footwear, these impact categories are amongst those classified as being of the most importance. The PEFCR also highlights Particulate matter, Acidification, Eutrophication of Freshwater and Resource use fossils as being of importance. These could thus also be included, but since it has not been within the scope of this project they will not be investigated. As seen in table 3.2, the chosen impact categories have been represented through three different characterization methods. Although Global Warming Potential can be represented through the ReCiPe midpoint H (2016) method, it uses IPCC (2013) to calculate GWP. We have chosen to represent it through the IPCC (2021) GWP100 method, since this method is newer and therefore more up to date. Furthermore, ReCiPe does not assess water depletion, but rather water consumption, why Berger et. al (2014) for water scarcity has been chosen. In the sensitivity check, an analysis of methods has been conducted to evaluate the impact of the chosen methods. To read further about each individual method, see Ecoinvent (2023).[1]

3.3 CUT-OFF CRITERIA FOR INITIAL INCLUSION OF INPUTS AND OUTPUT

To conduct this LCA study, a cut–off criteria of 1% has been set. This is inspired by the EPD guidelines.

The modelling is based on the cut–off version of Ecoinvent 3.8. To align allocation procedures with the database, a cut off on waste processing has been made based on economic allocation. This means that benefits from waste processing are attributed to the next product system, while certain burdens fall on the product system treated in this LCA study. This will be elaborated throughout the LCI.

Additionally, a range of assumptions as well as choices of exclusion have been made throughout the LCA study. These have been made based on availability of adequate data.

3.3.1 Assumptions for the LCA:

Assumption	Reasoning	Evaluation
All road transportation from the seaport in Portugal to the production facilities, and from distribution center to customers, are assumed to be distributed by a lorry 3,5 – 7,5 metric ton (applies both in the MTO and MP system).	The exact type of lorry is not known, so an assumption is necessary. The assumption is based on the type of product transported, as well as the number of products.	This is a conservative approach, and since this process does not contribute significantly to the overall results, it is found to be a reasonable choice.

[1] https://ecoinvent.org/the–ecoinvent–database/impact–assessment/#1661935753091–c04f8181–42cf

The detergent used in the use phase is based on the most used detergent globally (applies both in the MTO and MP system).	It is not possible to know the exact brands of detergent Son of a Tailor's customers use. Their customer base is global, why a global market has been used to estimate the brand of detergent.	The sensitivity analysis examines the effect the modelling of the detergent has and how sensitive the results are to this point. In this assessment the detergent process built for this LCA is measured against a generic soap process from Ecoinvent.
The energy used for a washing cycle in the use phase is based on a study from Bolius (2022) and it is assumed that the T–shirt is washed at 30ºC as stated in the care label (applies both in the MTO and MP system).	There is no available study on the use practices of Son of a Tailor's clients, and so an assumption is appropriate. Data on washing practices vary both in quality and availability. In addition to this, the way data on washing practices have been collected varies between data providers. Therefore, it was not possible to make a weighted average based on Son of a Tailor's customer base. Data from Bolius (2022) was chosen due to reliability and because it covers a market that reflects a portion of Son of a Tailor's customer base.	Energy–use of a washing machine varies depending on make and brand of the Machine. The source uses an average. Moreover, the source is Danish, and does not represent the geographical variety of Son of a Tailor's customer base. The sensitivity analysis investigates scenarios where different values for energy consumption influence the environmental impact.
It is assumed that the amount of laundry detergent used is equal to that recommended on the detergent bottle (applies both in the MTO and MP system).	Since we cannot know how much detergent is used, to be conservative it is assumed that a full measurement cup is used.	Since the measurement cup indicates how much laundry detergent to use, this assumption is reasonable. However, there can be some variety in use cases, and so this point will be examined in the sensitivity check.
It is assumed that the T–shirt does not get tumble dried in the use phase, but only washed and then air dried (applies both in the MTO and MP system).	There is no available data on the use practices of Son of a Tailor's customers, and so it is assumed that the customers follow instructions of the care label.	A sensitivity check will include the use of tumble–dryers to evaluate how it will affect the results of the use–phase.
The returned items in the MP system model are assumed to have an equal distribution between incineration, recycling, and landfill in their waste treatment (this applies only for the MP system).	The amount of data from the clothing industry on handling of returned items is low and lacking transparency.	The sensitivity of the results to this point will be investigated in the sensitivity check by investigating different waste scenarios.
The end–of–life scenarios for used T–shirts are based on	It is not possible to get adequate data on all the	The end–of–life scenarios will vary due to user

relevant literature for the markets that makes up 54,03 % of Son of a Tailor's market distribution (applies both in the MTO and MP system).	markets Son of Tailor cover, and so an assumption based on the majority is necessary.	behavior, and so this point will be examined in the sensitivity analysis. The sources used for the end-of-life scenario are found reasonable. The markets covered are found reasonable since it covers over 50%.
It is assumed that there is a 30% return rate for the MP system (this applies only for the MP system).	Since the modelling of the MP system is a scenario based on Son of a Tailor's production, and they have and has always had a MTO business model, there are no specific numbers for return rates at Son of a Tailor for an MP system. However, it can be assumed that return rates would not match Son of a Tailor's current return rates, since the MP business model does not afford custom made clothing. Due to this, return rates in the MP system are based on generic data.	The fashion industry has low data transparency, and so it is difficult to find data on this point. The data presented is the best that could be found at the time, but it is important to state that since not all of the generic data for the MP system are from the same source, there might be some discrepancies.
It is assumed that there is 20% overproduction in the MP system, resulting in deadstock (this applies only for the MP system).	In a MP system there will be some overproduction, since products are not made to order, meaning the number of products made is based on a forecast and not actual orders. This means that there will be some overproduction and products that cannot be sold.	The fashion industry has low data transparency, and so it is difficult to find data on this point. The data presented is the best that could be found at the time, but it is important to state that since not all of the generic data for the MP system are from the same source, there might be some discrepancies.
It is assumed that the returned T-shirts in the MP system are disposed of at the either the production site or the distribution site (this applies only for the MP system).	Since there is no specific data on handling of returned items in a mass production system, a conservative assumption that returned items are disposed in residual waste streams is made.	This is a conservative approach since cut-off at production sit is handled as recycling. Since it is unknown whether the returned items will go to the production site or the distribution site, this conservative approach with the residual waste streams has been applied. Finally, since this phase does not contribute significantly to the overall

		results, it is found to be a reasonable choice.
It is assumed that returned T–shirts that are disposed either at the production site or distribution site in the MP system are waste treated in an even distribution between recycling, incineration, and landfill (this applies only for the MP system).	There is no specific data available on waste treatment in a mass production system. Additionally, it was not possible to obtain adequate information on how Son of a Tailor's production site would handle returned T–shirts in this type of business model. Due to this, it is assumed that there is an even distribution of waste handling.	Other assumptions could have been made. For example, it could have been assumed that the T–shirts would be waste treated in the same way as cut–offs from the production. It could also have been assumed that it was treated as part of residual waste streams and a Portuguese mix could have been used. This uncertainty is handled in the sensitivity analysis. However, since the end–of–life of the returned T–shirt has no significant impact on the results, using the other assumptions will not have a relevant impact on the results.

Table 3.3 Assumptions for the LCA

3.3.2 Excluded processes:

Exclusion	Reasoning
The packaging between the harvesting of the Supima cotton and ginning process is not included.	Data on this comes from a third–tier supplier and is not available to Son of a Tailor.
The packaging between the ginning process and the dyeing and finishing process is not included.	Data on this comes from a third–tier supplier and is not available to Son of a Tailor.
The string on the hangtag and prints on the neck label, care label and hangtag of a T–shirt are not included.	These fall under the 1% cut–off criteria.
The transportation between cultivation, spinning and yarn production until the distributor's port in the US is not included.	Data on this comes from a third–tier supplier and is not available to Son of a Tailor.
The cardboard boxes used to transport the T–shirts from production to the washing facility is not included.	The cardboard boxes are owned by the washing company and are assumed to be reused many times due to the obvious wear and tear. A picture of the box can be viewed in inventory. Additionally, they fall under the 1% cut–off criteria.

The distribution to customers has been calculated from Son of a Tailor's logistic data from their distribution partner. This has created the basis for a weighted average of the markets where all transportation to locations that make up under 1% has not been considered.	A large amount of the destinations that Son of a Tailor distributes products to falls under 1% of their customer markets. The included distribution reflects 91,72% of Son of a Tailor's customers.
The packaging of detergent in the use phase is not included.	Data availability and quality is low. Additionally, it can be assumed that the impact from this is very low.
The transportation between the user and the potential end–of–life treatment and to a recycling facility is not included.	It is not possible to obtain exact information. This datapoint falls under the cut–of criteria.
Transportation of the returned items back to distribution center or production site in the mass production system is not included.	It is unknown whether the T–shirts will be returned to the production site or distribution center, and the mode of transport could also vary from that of the distribution phase. A conservative approach to exclude the transportation is employed. It is a conservative approach when compared to the MTO system, where there is also no transport of returned items due to the nature of the business model. Making this exclusion will give MP a more fair comparison to the MTO.

Table 3.4 Processes excluded from the LCA

4 LIFE CYCLE INVENTORY

The following section will describe the life cycle inventory used for this LCA study. It will describe how the data was collected, the quality of the collected data, the sources used, allocation, and how sensitive the data is. The section will also give a full description of what kind of input materials the product consists of, and how the MTO and MP models differentiate in terms of the inventory.

A generic overview of Son of a Tailor's production chain is shown in figure 4.1.

Lifecycle phase	Raw materials	Transport	Fabric knitting	Confect-ioning	Transport to distribution	Distribution	Use	End of life
Sub-phases	Supima cotton yarn, Care label, neck label, Hangtag, packaging box, and bioplastic bag	Transportation from raw material extraction to production	Knitting process, dyeing and finishing process	Cutting, sewing, ironing, heating and packaging	Transport to distribution center	Distribution to customers	Washing	Waste treatment of packaging, labels and T-shirt

Figure 4.1: Overview of life cycle phases and sub phases in study.

The data collection was conducted from December 2022 up until end of February 2023, giving a 3–month collection of data regarding e.g., a Son of a Tailor Supima cotton T–shirt. The data is however applicable for November 2022 to February 2023, meaning the data is based on a four–month period. According to Son of a Tailor the data from this period represent general production and are a good representation of their production practices. This period is chosen because it was the newest data at the time, and therefore the most representative of their current business model, which is why it is also considered a reasonable duration of data collection.

4.1 DATA QUALITY AND DESCRIPTION

The inventory for this analysis was created by Son of a Tailor collecting data from tier 1 and tier 2 suppliers (see appendix 2). Tier 1 are the suppliers of the final product, and tier 2 suppliers are manufacturers for the tier 1 suppliers. Additionally, generic data has been collected to create a scenario for business as usual for Mass Production of T–shirts. The data quality requirements have been to obtain as specific data as possible in relation to geographical, technological and time representation. Furthermore, the requirements have been to collect specific data for the operations where Son of a Tailor have financial or operational control, which in this case is in the confectioning phase as well as in the distribution phase. The data quality requirements have been inspired and followed in accordance to annex 5 in EN 15804:2012+A2:2019.

4.1.1 Data quality requirements – geographical representation

Ideally, the collected data should be as specific to Son of a Tailor's production as possible, meaning the geographical placements should be as specific as possible. For tier 1 suppliers, specific addresses have been obtained, and for tier 2 either region or country has been obtained. This means data quality on geographical representation for tier 1 and 2 suppliers is considered to be high. For Son of a Tailors customer market shares, distribution has been calculated based on country. Data on transport distances between tier 3 suppliers have not been possible to obtain and so the representation in that regard is low. However, processes from Ecoinvent have been chosen and modified to best match the representative of the geographical representation.

4.1.2 Data quality requirements – technological representation

The technology used to produce Son of a Tailor's T–shirt should be reflected in this study to match the actual processes. Since good data have been collected and provided by Son of a Tailor's production facility, it was possible to match the technological representation on a medium high level.

4.1.3 Data quality requirements – time representation

The data should match Son of a Tailor's current production practices and processes. Since the data used are of the newest available it can be assessed that the time representation is at a rather high level. Data in the use phase and end–of–life as well, has been selected to be as new as possible with most data in these phases being within five years.

4.1.4 Data quality assessment further comments

Data from tier 3 has been difficult to obtain, which is evident from the assumptions made in this LCA study (see section 3.3.1). Son of a Tailor have had good communication with the fabric knitting facilities as well as their own production in Portugal, and so an adequate amount of specific data for the different processes in the production could be obtained. Further data on the use phase have been obtained through external sources following generic average data, which is also evident from the assumptions.

For the background activities, which is where Son of a Tailor does not have any operational and financial control, processes based on secondary data sets from the Ecoinvent database 3.8 have been used. These processes have then been modified to match Son of a Tailor's production and product better. The applied processes are cut–off processes, meaning they use economic allocation.

All data used for this study has been methodically reviewed for aspects pertaining to technology, time, and geography, following the guidelines of ISO 14044 and evaluation is inspired from Annex E in EN 15804:2012+A2:2019. In Appendix 3, a list of collected generic data, as well as quality evaluation for each of these aspects, can be found. The processes chosen in Ecoinvent 3.8 have also been evaluated and classified for each of these aspects. This can also be found in Appendix 3. The data Son of a Tailor has collected from their suppliers has been assessed as true and the best quality available.

4.1.5 Allocation procedure

This LCA study uses the cut–off version of the Ecoinvent 3.8 database. The cut–off processes use economic allocation based on the principal 'polluters pay'[2]. To align with this, the rest of the modelling has also used economic allocation and cut–off processes. The allocation procedure has been the same for both the modelling of the MTO scenario and the MP scenario.

- To match Son of a Tailor's production and extraction of raw materials, a specific data set for the cotton harvesting and ginning process has been modified. Originally, a data set consisting of an energy mix from US, China, and India was used, but since Supima cotton is only produced in the US, the electricity and heat mix has been modified to only represent the US.
- The end–of–life scenarios for the T–shirt is built upon 54% of the geographical locations of Son of a Tailor's customer base. This created an incineration mix as well as a weighted average distribution for landfill and recycling for the primary locations of US, UK, Germany, and Denmark. The rest (46%) were allocated to the rest of world with basis in the US waste mix.
- In general, waste treatment in the EOL scenarios use Ecoinvent Cut–off processes, meaning that any benefits from the waste treatment are allocated to the next product system.
- To model recycling of cotton, an empty process has been used to comply with the allocation procedures in the cut–off version of the Ecoinvent database.

4.2 DIFFERENTIATION OF THE TWO BUSINESS MODELS

MTO and MP are the two systems analyzed in this study. All the processes going into the making of a T–shirt are the same in both business models. However, there is a difference: In MP the number of T–shirts produced will be determined by a sales forecast. This means that there is usually overproduction of items which then end up as deadstock. Data transparency is a general problem in the fashion and textile industry, which is why average values on deadstock have been difficult to obtain (Fashion revolution, 2022). Comprehensive research on the average deadstock produced has been conducted with various sources estimating different percentages. Based on the different sources' transparency of data, reliability, and use of external sources, a report from McKinsey and the Global Fashion Agenda has been deemed the most correct source of data.

The report "Fashion on climate – How the fashion industry can urgently act to reduce its greenhouse gas emissions" by McKinsey and the Global Fashion Agenda (Berg et. al, 2020) presents an analysis of the textile and fashion industry's greenhouse gas emissions, and points to areas where companies can focus their efforts to meet certain climate targets, including dealing with deadstock waste. According to McKinsey, the average overproduction resulting in deadstock in the textile industry is between 15–25%. Therefore, a middle value of 20% has been used as a basis for calculations.

Furthermore, an MP model does not accommodate the making of custom T–shirts, since mass production only affords standardized products. This means that they have larger rates of returns than

[2] Polluters pay principle is a guiding principle that suggests that the party responsible for producing pollution should be held accountable for it.

the MTO model, since there will be more cases of T–shirts not fitting the customers. This is backed up by numbers from Invesp (2022), stating that about 30% of clothing bought in e–commerce are returned (Invesp, 2022).

In Son of a Tailor's MTO model, they do not accept returns, but they do send a new T–shirt if the initial order does not fit. In this way they give the customer a remake guarantee. This means that in some cases there will be extra production. This is equivalated to returns since it still represents a source of overproduction. It is also unknown where the T–shirts that do not fit end up, and so it is assumed that they are disposed of by the client and end up in residual waste streams. The rate of returns for Son of a Tailor is 5,7%, and this number is based on their annual statistics of claim rates of all products from 2022 (see Appendix 4). For the differences between the two models MTO and MP, see table 4.1.

It is assumed that the remake guarantee would not be applied in the MP system, since the products would no longer be custom made to the client, so there would be no reason to guarantee fit. In this case, returns would be sent back to production or distribution center. Since there is no data with high transparency on how returned clothing items are handled at a production or stock site, we have chosen to model the waste treatment of returns in the MP system based on what happens to returned clothing from outlets. Returned clothes that are not sold in outlets at markdown are assumed to be treated with an equal distribution between recycling, landfill, and incineration in the end–of–life phase.

A validation of the different sources for both deadstock rate and return rates can be found in Appendix 3.

Process	MTO	Source	MP	Source
Deadstock	0%	Son of a Tailor	20%	Berg et. al, 2020
Return rates	5,7%	Son of a Tailor	30%	Invesp, 2022

Table 4.1: Differences between the two models, MTO and MP.

To model this, a baseline has been made. This baseline represents Son of a Tailor's MTO business model without return rates. To model the MTO business model with the extra T–shirts sent when the custom order does not fit, 5,7% has been added to the baseline.

To model the MP business model, the 20% deadstock has been added to the relevant life cycle phases of the MTO baseline. Furthermore, the 30% return rate has been added to the relevant life cycle phases. This way it represents the MP business model. Throughout the comparison of the models, the use phase is alike. In figure 4.2, a diagram of the added contributions for each phase and scenario is shown. Throughout this report, the allocations and choices will be elaborated more in depth, and the difference in the two scenarios will be made transparent.

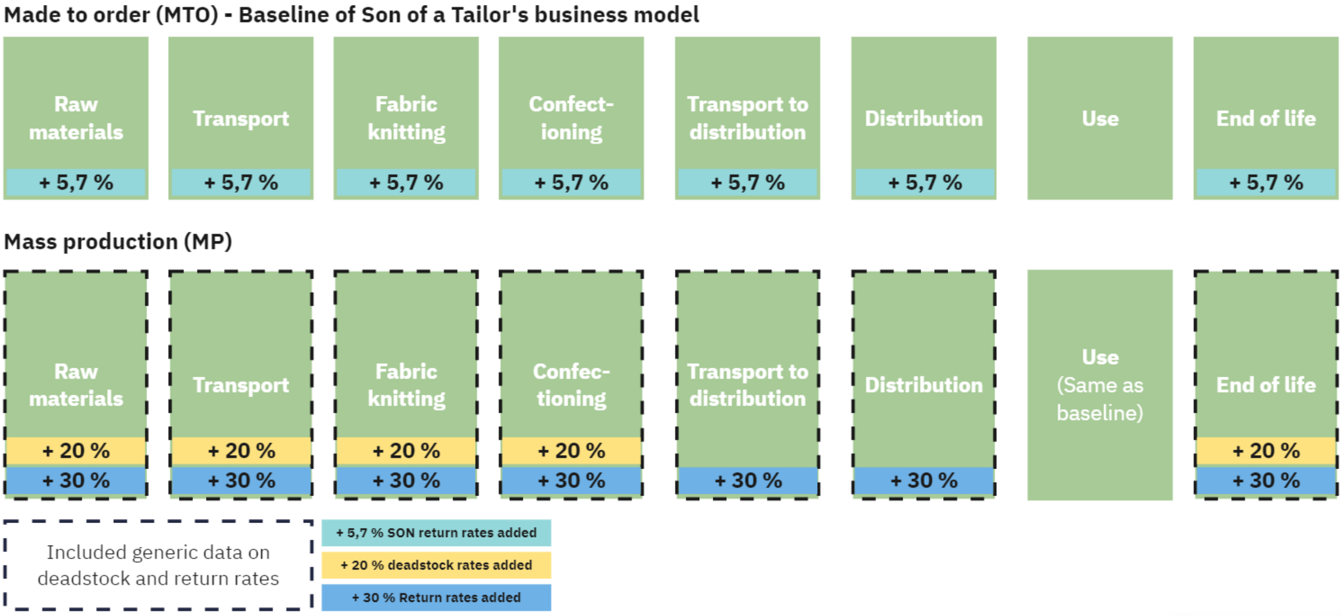

Figure 4.2 Overview of the differentiation between the two business models

Furthermore, the baseline of MTO business model will in the following be represented both without and with the 5.7 % return rates from Son of a Tailor. This is in order to give a transparent insight into the different data modelling steps. The differentiation is color-coded: green means *without return rates* and grey means *including return rates.*

4.3 RAW MATERIALS

In this phase all raw materials related to Son of a Tailor's Cotton T-shirt will be examined. The Cotton T-shirt is composed of 100% Supima Cotton fabric, a neck label, a care label, and a hangtag, and is packaged in a biobag and a cardboard box when sent out to customers. These components will be described and specified in this section. See table 4.2 and 4.3 for input data on raw materials.

The Supima cotton used for the T-shirt is OEKO-TEX® STANDARD 100 certified. This means that the fabric has been tested for a list of several hundred toxic chemicals (Oeko-Tex, 2023). Supima is a non-profit promotional organization of the American Pima Cotton producer, and the global steward of the SUPIMA® trademark. With their SUPIMA® licensing program, they engage the entire supply chain from grower to brand/retailer. Since the 1980s they have run a yearly licensing process done by an industry standard evidentiary documentation. In this process they do true origin verification, done by Oritain who creates a geo-chemical fingerprint of the cotton. They are also big on transparency and have a full digital model for traceability and transparency. This means that when buying a Supima product, you are completely sure of the authenticity and quality of the fiber as well as who has responsibility in the supply chain (Supima, 2023).

Supima cotton is naturally white, so it does not need to be bleached or dyed for the purpose of producing a cotton T-shirt. However, since Son of a Tailor's cotton T-shirt goes through a dyeing phase it is added to the study (Supima, 2023).

All Supima cotton is grown in US, with 93% being grown in California, 3% in Arizona, 2% in New Mexico, and 2% in Texas. Production of Supima cotton starts by farming cotton seeds. Before harvesting the cotton, the seeds have naturally absorbed different levels of chemicals, isotopes, and water. The cotton is then harvested, ginned, and pressed, processes in which lint and trash are removed and the cotton is pressed into bales. After this, the cotton is spun into yarn. All of this is done in America (Supima, 2023).

The knitting, dyeing, and finishing of the cotton is done at one of Son of a Tailor's suppliers in Portugal and will be elaborated in the fabric knitting section 4.6.

The neck label is made from 0,18 grams of 100% recycled satin polyester. One neck label is sewn into each T–shirt production in Portugal. The supplier informs us that the origin of the material is in Turkey. The print on the neck label is excluded from the LCA study, due to the low impact.

The care label is made from 0,47 grams of 100% recycled satin polyester, and like the neck label it is also sewn into the T–shirt by hand. The supplier informs the care label are from China. The total weight of the care label is 0,47 grams and one care label is added to each T–shirt. The print on the label is excluded from this LCA, due to its low impact.

A hangtag is attached to each T–shirt by tying it on with a piece of string. The hangtag is made from 4,22 grams of FSC mix certified cardboard, and is produced in Turkey from the same supplier as the care label and neck label, FSC mix is a FSC certification, which means that at least 70% of the forest–based parts of a material are either materials from FSC certified forests, controlled wood/FSC Controlled Wood or reused materials (dk.fsc.org, 2022). The string used to tie on the hangtag is excluded from this LCA, due to its low weight.

For **the packaging** of the cotton T–shirt one biobag and one cardboard box are used per item.

The biobag is made from 5,9 grams of 100% biodegradable polylactic acid biopolymer (PLA) film with treatment. The biobag is produced in Portugal has a certificate on its compostability and biodegradability through Ecovio F23B1 certification.

The Box is made of 100% FSC mix certified cardboard. The total weight of the box is 76,8 grams. It is supplied from Poland, which is also the origin of the material.

Raw material – MTO business model				
Process	**Material**	**Amount**	**Unit**	**Source**
Yarn, cotton, yarn production, (ring, spinning, for knitting) + Fibre production (ginning)	Supima cotton	181,35	g	Son of a Tailor
Waste polyethylene terephtalate, for recycling	Neck label	0,18	g	Son of a Tailor
Waste polyethylene terephtalate, for recycling	Care label	0,47	g	Son of a Tailor
Solid bleached and unbleached board carton	Hangtag	4,22	g	Son of a Tailor
Polyactide, granulate	Biobag	5,9	g	Son of a Tailor
Solid bleached and unbleached board carton	Packaging box	76,8	g	Son of a Tailor
	SUM	**268,92**	**g**	

Table 4.2 Input data about product composition per functional unit including packaging.

Raw material – MTO business model with 5,7% returns

Process	Material	Amount	Unit	Source
Yarn, cotton, yarn production, (ring, spinning, for knitting) + Fibre production (ginning)	Supima cotton	191,69	g	Son of a Tailor
Waste polyethylene terephtalate, for recycling	Neck label	0,19	g	Son of a Tailor
Waste polyethylene terephtalate, for recycling	Care label	0,50	g	Son of a Tailor
Solid bleached and unbleached board carton	Hangtag	4,46	g	Son of a Tailor
Polyactide, granulate	Biobag	6,24	g	Son of a Tailor
Solid bleached and unbleached board carton	Packaging box	81,18	g	Son of a Tailor
	SUM	**284,26**	**g**	

Table 4.3 Input data about product composition per functional unit including packaging (incl. return rates).

As seen in table 4.2 and 4.3, the recycled polyester satin fabric has been modelled with a waste process to streamline allocation procedures of the cut–off version of Ecoinvent 3.8. These processes contribute with benefits to the system, but not with burdens.

The data provided from Son of a Tailor shows the Supima cotton input per T–shirt is 147,55 g but since 33,8 g is cut off in the confection phase, this needs to be added to the reference flow:

$$Input\ of\ Supima\ cotton\ per\ t-shirt = 147{,}55g + 33{,}8g = 181{,}35$$

For the MTO with return rates, 5,7% is added to the 181,35g giving 191,69g Supima cotton per T–shirt.

4.4 TRANSPORT

All materials for the cotton T–shirt are delivered to the production in Portugal. The transportation of the Supima cotton has been calculated from a US seaport to the production facilities in Portugal. We have chosen to calculate from Houston port, since there was a relevant freight route to Portugal, and the production is placed in the southern part of the US. Since the cotton is produced and cultivated in various states, the transportation from the cultivation, spinning and yarn production until the distributors port is not considered in the analysis due to a lack of transparency in the supply chain.

When the Supima cotton arrives in Porto seaport it is transported to the production by truck. See the input of these transportation steps in table 4.4 and 4.5.

The upstream transportation of the neck label, care label, hangtag, biobag and the packaging box from sub–suppliers is not included in the LCA Study.

Transport to production – MTO business model				
Process	**Distance**	**Amount**	**Unit**	**Source**
Sea freight, Container ship	from Houston port (US) to Porto port (PT)	1813,86	kg.km	Identified by routescanner.com
Freight, lorry 3.5–7.5 metric ton, EURO 6	from Porto Port to production facilities	9,19	kg.km	Identified by Google maps

Table 4.4: Input data about transportation to production per functional unit

Transport to production – MTO business model with 5,7% returns				
Process	Distance	Amount	Unit	Source
Sea freight, Container ship	from Houston port (US) to Porto port (PT)	1917,25	kg.km	Identified by routescanner.com
Freight, lorry 3.5–7.5 metric ton, EURO 6	from Porto Port to production facilities	9,72	kg.km	Identified by Google maps

Table 4.5: Input data about transportation to production per functional unit (incl. return rates)

The sea freight distance was measured to be 10002 km and giving that the Supima cotton weighs 181,35 g as input, the kg.km is calculated as follows:

$$Sea\ freight = 0{,}18135\ kg * 10002\ km = 1813{,}86\ kg.km$$

The same procedure applies to the lorry freight multiplying the weight of the Supima cotton input with the distance.

For the MTO with 5,7 % return rates the extra weight is added multiplied with the distance as per the following example:

$$Sea\ freight = 0{,}19169\ kg * 10002\ km = 1917{,}25\ kg.km$$

4.5 FABRIC KNITTING

The Supima cotton is made into fabric by knitting the yarn on an industrial machine in Portugal. The knitting process is classified as a circular knitting process where yarn is fed into a machine and cams then knit the yarn together. When knitted this way, a tube of fabric is created. The tube is flattened and wound onto a cardboard roll (Duhovic et. al., 2011, p. 171–192). See figure 4.4 and figure 4.5. During the knitting process, knitting/weaving oil is used. Son of a Tailor have been identifying the specific amount of knitting oil being used, a number that has been modified into the knitting process. One knitting machine consumes 1000 liters for production of 630,000 kg fabric, and therefore it takes 0,00028 liters to produce 181,35 g Supima cotton, corresponding to the input for the MTO without return rates.

After the knitting process, the fabric goes to a dyeing and finishing treatment. This treatment uses electricity, natural gas, dyeing chemicals, and water. The used dyeing chemicals are Acetic acid, Inorganic chemicals, Soda ash (heptahydrate), and Sodium sulfate (anhydrite), which are specified by a secondary data from dyeing and finishing process in Ecoinvent 3.8.

The dyeing and finishing process is done a facility 7,7 km from the fabric knitting production. The transportation between these facilities has been mapped out and calculated. The transportation is done by the suppliers own van, which has EURO class 6 and transports around 500 kg of fabric between the facilities. During the distribution between the two facilities, no packaging is used.

Figure 4.3: Circular knitting machine **Figure 4.4:** Fabric roll

For the data collection on the fabric knitting phase and the following confectioning phase, Son of a Tailor have been in contact with supplier in Portugal where they have provided the data necessary for conducting the LCA study. See table 4.6 and 4.7. for input data on the fabric knitting phase. This means that primary data for these phases has been used. To calculate the locations–based emissions of the electricity usage in Portugal for fabric knitting and the following confectioning phase, the calculations are based on the geographical energy mix (EDP, 2023). See the energy mix for Portugal in figure 4.5.

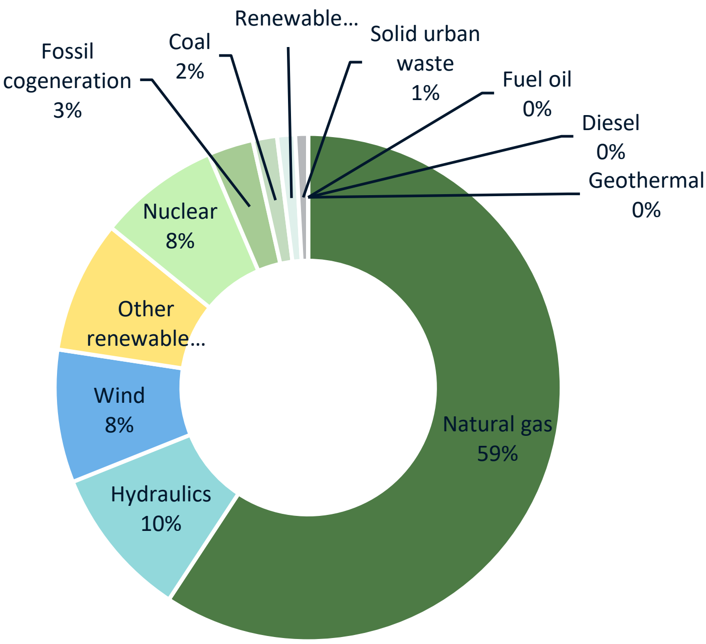

Figure 4.5: The geographical energy mix for Portugal (EDP, 2023).

Fabric knitting – MTO business model Process	Amount	Unit	Source
Circular knitting process, electricity	0,05	kWh	Son of a Tailor
Dyeing and finishing process, electricity	0,21	kWh	Son of a Tailor
Dyeing and finishing process, heating, natural gas	1,89	kWh	Son of a Tailor
Dyeing and finishing process, Water use	18,67	Liter	Son of a Tailor
Freight, light commercial vehicle, Transport from knitting to dyeing production	1,4	kg.km	Son of a Tailor
Transport, freight, light commercial vehicle, dyeing to confectioning	9,12	kg.km	Son of a Tailor

Table 4.6: Input data for fabric knitting phase per functional unit.

MTO business model with 5,7% returns Process	Amount	Unit	Source
Circular knitting process, electricity	0,05	kWh	Son of a Tailor
Dyeing and finishing process, electricity	0,22	kWh	Son of a Tailor
Dyeing and finishing process, heating, natural gas	2	kWh	Son of a Tailor
Dyeing and finishing process, Water use	19,74	Liter	Son of a Tailor
Transport, Freight, light commercial vehicle, Transport from knitting (SON Supply) to dyeing production	1,48	kg.km	Son of a Tailor
Transport, freight, light commercial vehicle, from dyeing to confectioning	9,64	kg.km	Son of a Tailor

Table 4.7: Input data for fabric knitting phase per functional unit (incl. return rates)

Different values for energy and water use were provided From Son of a Tailor's supplier information, which made it possible to calculate these values to the reference flow:

- Electricity, fabric knitting = 0,28 kWh/kg
- Electricity, dyeing and finishing = 1,15 kWh/kg
- Natural gas, dyeing and finishing = 10,44 kWh/kg
- Water, dyeing and finishing = 103 litres/kg

To calculate these values to the corresponding reference flow, the values were multiplied with the amount of Supima cotton, see calculation example below:

$$electricity, fabric\ knitting\ per\ t-shirt = 0{,}28\frac{kWh}{kg} * 0{,}18135\ kg = 0{,}05\ kWh$$

This is for the refence flow without return rates. With the return rates, an additional 5,7% weight would be added to the calculation.

4.6 CONFECTIONING

In the making of the T–shirt, a range of processes are followed. First the fabric is cut into pattern parts by a cutting machine, then the pattern parts are sewn together. Before the T–shirt is packaged and shipped, it is washed in an industrial washing machine, tumble dried and lastly ironed.

The energy used for these production processes has been estimated based on electricity invoices. The invoices differ between summer and winter, in terms of how much energy should be allocated to Son of a Tailor. An average has been made with data from November 2022, December 2022, January 2023, June 2022, and July 2022. This gave us an average of the total energy spent for all production, of which 24% is Son of a Tailor's production share. From invoices and production volume in November, December, and January it was calculated that an average of 2024 items per month is produced for Son of a Tailor's production. The average amount of energy used per item is then 0,26 kWh. The inputs for these processes can be seen in table 4.8 and 4.9. See calculations below:

- Items produced in November: 2205
- Items produced in December: 1578
- Items produced in January: 2291

Total items produced: 6074

- Energy used in November: 1218 kWh
- Energy used in December: 2543 kWh
- Energy used in January: 2913 kWh

Total energy used: 6674 kWh

Since the supplier have provided data showing that Son of a Tailor accounts for 24 percent of the production share, the energy allocated to Son of a Tailor's T–shirt is:

$$Allocated\ energy = 6674\ kWh * 0{,}24 = 1601{,}76\ kWh$$

This means that the energy use per T–shirt is as follows:

$$Energy\ use\ per\ t-shirt = \frac{1601{,}76\ kWh}{6074\ t-shirts} = 0{,}26\ kWh\ per\ t-shirt$$

For the washing process, the T–shirts are driven back and forth to a washing facility. They are transported in a van, either a Ford Transit or Mercedes Sprinter from 2014. The Euro class of vans was not possible to identify, but since they are from 2014 there is indication that the vans have a Euro class 5 (RAC.co.UK, 2023). The T–shirts are being transported in cardboard boxes which are assumed to be reused. The trip to the washing facility is approximately 4,3 km, and for each trip between 25 to 100 items are transported. At the washing facility, the T–shirts are washed in an industrial washing machine from GIRBAU model HS–3055 with no chemicals. From the machine's product specification 6.4 kW is used per hour with about 50 T–shirts per wash cycle. A wash cycle is about 30 min and 7L of water per 10 kg are used. This means that for one T–shirt, 0,11 kWh and 0,103 Liters of water are used.

Figure 4.6: Box used for transport of T–shirts to wash

Calculation of these values can be viewed in the following:

Transport to washing facility is 4,3 km and a T–shirt weighs 0,1482 kg, meaning that the kg.km is:

$$Transport\ to\ washing\ facility = 4{,}3\ km * 0{,}1482\ kg * 2 = 1{,}27\ kg.km$$

The reason for multiplying with 2 is that the T–shirt needs to be transported back to production as well.

The electricity use of the washing machine was 6,4 kw and 50 t–shits are washed per cycle. The amount of T–shirts per cycle is:

$$kg\ t - shirt\ per\ cycle = 50 * 0{,}1482\ kg = 7{,}41\ kg\ t - shirts\ per\ cycle$$

The kwh use per cycle is 6,4 kw multiplied with 0,5, since a washing cycle lasts 30 min.

$$kWh\ per\ cycle = 6{,}4 * 0{,}5 = 3{,}2\ kWh$$

This means that per kg T–shirt, the kWh use per washing cycle is:

$$kWh\ per\ kg\ t - shirt = \frac{3{,}2kWh}{7{,}41\ kg\ t - shirt} = 0{,}43\ kWh\ per\ kg\ t - shirt$$

Since a T–shirt weighs 0,1482 kg, the kWh per T–shirt is:

$$kWh\ per\ t - shirt = 0{,}43 * 0{,}1482 = 0{,}06\ kWh\ per\ t - shirt$$

This calculation example is for MTO without return rates. With return rates the 5,7 % would be added.

Calculation for the kWh use for the dryer is made based on the machine specification:

Voltage = 400

Ampere = 200

Hours per drying = 0,5

$$kwh\ per\ drying\ cycle = \frac{400 * 200 * 0{,}5}{1000} = 4\ kWh$$

50 items are dried at a time, meaning that the kWh per kg T–shirt is:

$$kWh\ per\ kg\ t - shirt = \frac{4\ kWh}{7{,}41\ kg\ t - shirt} = 0{,}54\ kWh\ per\ kg\ t - shirt$$

Since a T–shirt weighs 0,1482 kg, the kWh per T–shirt is:

$$kWh\ per\ t - shirt = 0{,}54 * 0{,}1482 = 0{,}08\ kWh\ per\ t - shirt$$

This calculation example is for MTO without return rates. With return rates the 5,7 % would be added.

Confectioning – MTO business model			
Process	**Amount**	**Unit**	**Source**
Electricity heat for production processes cutting, sewing, ironing, and heating, production mix.	0,263	kWh	Son of a Tailor
Water usage, washing process	0,103	L	Son of a Tailor
Electricity, washing process	0,06	kWh	Son of a Tailor
Electricity, drying process	0,08	KWh	Son of a Tailor
Transport to washing facility, light commercial vehicle	1,27	kg.km	Identified with Google maps

Table 4.8: Input data for MTO's confectioning processes and transport per functional unit

Confectioning – MTO business model with 5,7% returns			
Process	**Amount**	**Unit**	**Source**
Electricity heat for production processes cutting, sewing, ironing, and heating, production mix.	0,28	kWh	Son of a Tailor
Water usage, washing process	0,116	Liter	Son of a Tailor
Electricity, washing process	0,063	kWh	Son of a Tailor
Electricity, drying process	0,084	KWh	Son of a Tailor
Transport to washing facility, light commercial vehicle	2,41	kg.km	Identified with Google maps

Table 4.9: Input data for MTO's confectioning processes and transport per functional (incl. return rate)

4.6.1 Waste related to production

There is waste related to cutting the fabric. This happens when the pattern does not perfectly fill out the fabric roll. Based on data from 2022, it is estimated that 77,2% of the fabric is utilized and 22,8% is wasted. This means, that per 147,55 g T–shirt (without care and neck label), 33,8 grams of the cotton is waste fabric is sent to recycling. The cut of waste fabric it being sent to the recycling facility. This facility sorts the received textiles, makes it into bales and sends it to a shredding facility.

Figure 4.7: Shredded recycled textiles.

The end–product can be used for isolating buildings, geotextile rugs, car seat filling, mattress filling, and much more. In the modelling of this recycling process, an empty process has been used in order to comply with the allocation methods in the cut–off version of the Ecoinvent database.

In addition to the fabric waste, there is waste cardboard from the internal cone of the fabric roll. This carboard material is treated as waste paperboard, which typically goes to incineration.

Waste related to production – MTO business model			
Process	**Amount**	**Unit**	**Source**
Waste fabric to recycling per T–shirt	0,0338	kg	Son of a Tailor (2023)
Waste cone for fabric	0,0036	Kg	Son of a Tailor (2023)

Table 4.10: Input data for the waste created in the production per functional unit.

Waste related to production – MTO business model with 5,7% return rates			
Process	**Amount**	**Unit**	**Source**
Waste fabric to recycling per T–shirt	0,0357	kg	Son of a Tailor (2023)
Waste cone for fabric	0,0038	Kg	Son of a Tailor (2023)

Table 4.11: Input data for the waste created in the production per functional unit (incl return rates).

The only other waste related to the confectioning phase is the cardboard fabric roll which the cotton fabric arrives on (see figure 4.5). The rolls arrive uncovered, making the cardboard rolls the fabric is wound onto the only waste.

4.7 TRANSPORT TO DISTRIBUTION

After the T–shirt is sewn and packaged in Portugal, it is sent to Son of a Tailor's distribution center in Brøndby, DK. To get to the distribution center, it is first transported by DHL to the Airport, Aeroporto Francisco Sá Carneiro in Porto, which is approx. 40,7 km from the production facilities. It is mainly distributed with a van of the Opel Movano make, EURO class 6, which ships around 150–200 items per day. From the airport in Porto, the packaged items are flown to Copenhagen Airport. Lastly, the packaged items are transported by van from Copenhagen Airport to the distribution center in Brøndby. The van is the Iveco model, EURO class 6. Since there is a level of uncertainty as to whether DHL drives directly to and from the Son of a Tailor facilities in Brøndby, we have chosen to model the transport with 3.5–7.5 tons lorry with Euro class 6. This is a bigger vehicle than the DHL van, but it has been chosen to give a more conservative estimate.

The calculations for kg.km were to sum the weight of T-shirt, biobag, hang tag, care label, neck label and cardboard box and then multiply it with the distance. As an example, the distance to the airport is 40,7 km and the weight of the full product is 0,23512 kg

$$40{,}7\ km * 0{,}23512\ kg = 9{,}57\ kg.km$$

Figure 4.8 The van for the transportation between SON Supply facilities to the DHL airport in Porto (left) and the distribution packaging (right).

Transport to distribution – MTO **business model**				
Process	**Distance**	**Amount**	**Unit**	**Source**
Freight, lorry 3.5–7.5 metric ton, EURO 6	From production to Airport, Portugal	9,57	kg.km	Identified by Google maps
Freight, aircraft, medium haul	From Airport –Aeroporto Sá Carneiro, Porto to Copenhagen Airport	522,86	kg.km	Identified by distance.to
Freight, lorry 3.5–7.5 metric ton, EURO 6	From Copenhagen Airport to Distribution center in Brøndby, Denmark	4,44	kg.km	Identified by Google maps

Table 4.12: Input data for the transport to distribution center per functional unit

Transport to distribution – MTO **business model** with 5,7% returns				
Process	**Distance**	**Amount**	**Unit**	**Source**
Freight, lorry 3.5–7.5 metric ton, EURO 6	From production to Airport, Portugal	10,11	kg.km	Identified by Google maps
Freight, aircraft, medium haul	From Airport –Aeroporto Sá Carneiro, Porto to Copenhagen Airport	552,66	kg.km	Identified by distance.to
Freight, lorry 3.5–7.5 metric ton, EURO 6	From Copenhagen Airport to Distribution center in Brøndby, Denmark	4,7	kg.km	Identified by Google maps

Table 4.13: Input data for the transport to distribution center per functional unit (incl return rates)

4.8 DISTRIBUTION

For the distribution to customers, Son of a Tailor have provided information on the mode of transport used and which markets they distribute to (see Appendix 2, worksheet 'Logistics B2C'). The percentage of the market distribution has been considered when calculating the average distance a T–shirt must travel before reaching the customers. To calculate the average distance, we have used estimates from the web–based distance calculator distance.to for air travel and Google maps for road travel. The distance has been calculated for each country based on the distance from the distribution center in Brøndby to the largest city of each country. For the weighted average of all international distribution, all transportation to location under 1% has not been considered. This means that the distribution used to calculate the distribution to customers reflects 91,72% of the sold items. To make this representative of 100% of the transportation, the distribution for each geographical location was weighted (see equation).

$$\frac{Distribution}{SUM\ of\ distribution} \cdot 100 = weighted\ distrubution$$

For example, one market received 9,08% of total products sent by road. This was weighted to 9,90%, see calculation below.

$$\frac{9{,}08\%}{91{,}72\%} \cdot 100 = 9{,}90\%$$

The weighted distribution is then used to calculate distance according to the weighted distribution.

$$\frac{1242km \cdot 9{,}90\%}{100} = 0{,}13\ km$$

Distribution – MTO business model				
Process	Distance	Amount	Unit	Source
Transport, freight, aircraft, medium haul	Transport to customers by airplane	800,9	kg.km	Identified by distance.to
Transport, freight, lorry 3.5–7.5 metric ton, EURO 6	Transport to customers by truck	34,87	kg.km	Identified by Google maps

Table 4.14: Input data for the distribution per functional unit

Distribution – MTO business model with 5,7% returns				
Process	Distance	Amount	Unit	Source
Transport, freight, aircraft, medium haul	Transport to customers by airplane	846,55	kg.km	Identified by distance.to
Transport, freight, lorry 3.5–7.5 metric ton, EURO 6	Transport to customers by truck	36,85	kg.km	Identified by Google maps

Table 4.14: Input data for the distribution per functional unit

4.9 USE

For the use phase, different sources of literature were investigated for information regarding how many washing cycles a T–shirt typically has in its life span, how much energy is used per washing cycle, how much water is used per washing cycle, and how and what type of detergent is used per washing cycle.

4.9.1 Lifespan

The lifespan of a T–shirt is measured by its technical specifications on how many washes it can withstand. Son of a Tailor has had the Supima cotton fabric tested by the Danish Technological Institute, and the full test and results can be seen in Appendix 1. Therefore, it is estimated that Son of a Tailor's T–shirt can be washed 26 times before it is discarded, which is 50% more than the average T–shirt. This lifespan is based on a global average of 17,3 total washes for a T–shirt, which is conducted from a research project on quantifying apparel consumer use behavior in six different countries (Daystar et al. 2019).

4.9.2 Washing

The washing process requires water, electricity, and laundry detergent. It is assumed that the laundry detergent used is Tide, since this is the most used detergent globally (Polaris, 2021). Tide recommends using 40 ml detergent for 1 wash (Tide, 2020). The care label instruction of washing on 30ºc is assumed to be followed. Amount of clothing per wash is estimated to be 3.2kg based on numbers from the Danish Energy Agency (Danish Energy Agency, 2023). For one wash approximately 0,48 kWh and 44 liters of water is needed (Bolius, 2022; Project Zero, 2019).

Process	Amount	Unit	Source
Clothing per wash	3,2	kg	Energistyrelsen (2023)
Laundry detergent used	Tide		Polaris (2021)
Detergent per wash	40	ml	Tide (2020)
Energy per wash	0,45	kWh	Bolius (2022)
Water per wash	44	Liter	Project Zero (2019)

Table 4.15 Input data for the use phase

The input data for the use phase per functional unit is shown in table below:

Process	Amount	Unit	Source
Detergent per wash	50,96	g	Tide (2020)
Energy per wash	0,54	kWh	Bolius (2022)
Water per wash	52,98	Liter	Project Zero (2019)

The calculation for the input data for the use phase per functional unit has been as followed:

$$\textbf{Energy use per washed t} - \textbf{shirt} = \frac{\textbf{0,45 kWh}}{\textbf{3,2 kg}} * \textbf{0,1482 kg} = \textbf{0,0208 kWh}$$
$$\textbf{Energy use per life time of t} - \textbf{shirt} = \textbf{0,0208 kWh} * \textbf{26} = \textbf{0,54 kWh}$$

$$\textbf{Water use per washed t} - \textbf{shirt} = \frac{\textbf{44 liter}}{\textbf{3,2 kg}} * \textbf{0,1482 kg} = \textbf{2,03}$$
$$\textbf{Water use per life time of t} - \textbf{shirt} = \textbf{2,03} * \textbf{26} = \textbf{52,98 liter}$$

$$\textbf{Laundry detergent use per washed t} - \textbf{shirt} = \frac{(\textbf{40 ml} * \textbf{1,058}^{3})}{\textbf{3,2 kg}} * \textbf{0,1482 kg} = \textbf{1,95 g}$$

$$\textbf{Landry detergent use per life time of t} - \textbf{shirt} = \textbf{1,95 g} * \textbf{26} = \textbf{50,96 g}$$

4.10 END-OF-LIFE

To model the end–of–life phase of the T–shirt, the waste treatment of textiles for Son of a Tailor's four main markets were used to investigate different scenarios. It was found that textiles are either sent to incineration, landfill or recycling, and a mix of these three are used in this LCA study.

Additionally, the end–of–life phase differs within the MTO system and the MP system. In the MTO system, the responsibility of handling the returned items falls on the customer, and since the customer is sent a new t–shirt, and the item that did not fit is still in the care of the customer. This differs from the MP system, in which items are assumed to be returned to the production or distribution site, and then it is Son of a Tailor's responsibility to handle the returned items. This difference occurs based on the difference in the two business models which is further elaborated in section 4.2.

4.10.1 Return rates

Son of a Tailor does not accept returns. If a customer's T–shirt does not fit, they will receive a new T–shirt with a corrected fit. This is called Free Remake Guarantee (FRG). Since this is also a type of overproduction, we have accounted for this as a return, which means extra production costs. Son of a Tailor estimates that they send extra T–shirts in 5,7% of cases. This is based on their annual statistics of claim rates of all products from 2022 (see Appendix 4).

In the modelling, it is assumed that a T–shirt that does not fit, which would normally be returned, is discarded by the customer. The T–shirt will then go into residual waste streams, and so the waste for this is accounted for in the waste scenario in the end–of–life phase.

4.10.2 Waste scenarios

Waste scenarios for the T–shirt have been modelled by creating a waste scenario that allocates waste treatment between incineration, landfill, and recycling. This allocation is based on generic data covering the waste treatment of textiles from four markets These countries have been chosen based on data availability, and in addition to this, these markets cover 54% of the customer base.

Given that the waste scenarios reference different sources, there is some variation in which datapoints are presented in each source. To address this, we opted to focus on waste categories shared across the sources: landfill, recycling, and incineration. The scenarios were then calculated based on normalized datapoints for each of these categories in each of the markets.

For each of the covered markets, the datapoints were normalized to represent 100% of the waste treatment in that market. This normalization was achieved using the following equation:

$$\frac{Waste\ distribution\ from\ source}{Sum\ of\ wastedistributions\ from\ the\ source} \cdot 100 = Weighted\ distribution$$

[3] This is the relative density of the laundry detergent. It is used to convert the ml to g.

For instance, one scenario, the combined distribution of the selected waste categories equated to 93,63%. By normalizing the datapoints, we scaled it to a total of 100%. For example, there is 25,53% incineration in one scenario according to the source, which was weighted to 27,27% using the formula:

$$\frac{25{,}53\%}{93{,}62\%} \cdot 100 = 27{,}27\%$$

With the weighted distribution determined, we then calculated the amount of allocated T–shirt waste for each waste category in each market. This was achieved by employing the corresponding weighted market share for that market.

To calculate the weighted market share for each country, similar to the distribution weighting process, we utilized the equation:

$$\frac{Marketshare\ per\ country}{Sum\ of\ marketshares} \cdot 100 = Weighted\ market\ share$$

For example, one market share is 9,34% and the sum of market shares is 54,03%, then the weighted market share is:

$$\frac{9{,}34\%}{54{,}03\%} \cdot 100 = 17{,}29\%$$

Consequently, for that scenario, the allocated weight of T–shirt waste can be calculated as follows:

$$Allocated\ t - shirt\ waste = 17{,}29\% \cdot 27{,}27\% \cdot 148{,}2g = 6{,}99g$$

By following these calculations, we can effectively estimate the allocated T–shirt waste for each waste category in different markets.

To model the waste scenarios, Nation specific processes have been used in the cases where they are available in Ecoinvent 3.8. In cases where nation specific process are not available, processes for Rest of World have been used. Recycling of the T–shirts is handled by an empty process to align the allocation procedures with the cut–off version of the Ecoinvent 3.8 database. Waste treatment of the biobag, cardboard box and hangtag are not allocated based on the customer base, since there are no nation specific processes available. The input data used for waste modelling can be seen in table 4.16.

Table 4.17 provides an overview of the selected sources and waste data for the end–of–life scenario for the MTO business model.

Process	Amount	Unit	Source
Return rates	5,7	%	Son of a Tailor
Waste fabric	22,8	%	Son of a Tailor, Data from all production made in 2022
Deadstock	0	%	Son of a Tailor
Market one Incineration rate	18,9	%	Cao et. al. (2022)
Market one Landfill rate	66,4	%	Cao et. al. (2022)
Market one Recycling rate	14,7	%	Cao et. al. (2022)
Market two Incineration rate	7	%	FOEE (2020)
Market two Landfill rate	31	%	FOEE (2020)

Market two Recycling rate	14	%	FOEE (2020)
Market three Incineration rate	25,53	%	Labfresh (2020)
Market three Landfill rate	57,45	%	Labfresh (2020)
Market three Recycling rate	10,64	%	Labfresh (2020)
Market four Incineration rate	55,93	%	Watson et. al. (2018)
Market four Landfill rate	38,15	%	Watson et. al. (2018)
Market four Recycling rate	0,43	%	Watson et. al. (2018)

Table 4.17: Overview of sources for waste data in end–of–life scenarios.

4.11 MASS PRODUCTION INVENTORY

To model the MP business model without return rates, 20% has been added to some of the phases of the MTO baseline distribution, to represent the overproduction associated with an MP business model. On top of this, an extra 30% has been added to some of the phases, to model a scenario for MP business model with return rates. The 30% return rates are counted as extra production per T–shirt.

In this section, the inventory for the MP business model will be explained, and it will be apparent where it differs from the MTO business model.

4.11.1 Raw materials

The raw material input for the MP with returns is the same as for the MTO, but with the addition of deadstock and return rates.

Material	Amount	Unit	Source
Supima cotton	272,03	g	Son of a Tailor
Neck label	0,27	g	Son of a Tailor
Care label	0,71	g	Son of a Tailor
Hangtag	6,33	g	Son of a Tailor
Biobag	8,85	g	Son of a Tailor
Packaging box	115,2	g	Son of a Tailor
SUM	**403,39**	**g**	

Table 4.18: Input data for raw materials per functional unit (incl return rates).

4.11.2 Transport

The transport to the production is the same as in MTO, but with the addition of 20% overproduction and 30% return rates.

Process	Distance	Amount	Unit	Source
Sea freight, Container ship	From Houston port (US) to Porto port (PT)	2720,79	kg.km	Identified by routescanner.com

Transport, Freight, lorry 3.5–7.5 metric ton, EURO 6	From Porto Port to production facilities	13,79	kg.km	Identified by Google maps

Table 4.19: Input data for transportation to production per functional unit (incl return rates).

4.11.3 Fabric knitting

The fabric knitting phase uses the same input as MTO, but 20% is added for overproduction and 30% is added for returns.

Process	Amount	Unit	Source
Circular knitting process, electricity	0,11	kWh	Son of a Tailor
Dyeing and finishing process, electricity	0,47	kWh	Son of a Tailor
Dyeing and finishing process, heating, natural gas	4,25	kWh	Son of a Tailor
Dyeing and finishing process, Water use	42,02	Liter	Son of a Tailor
Transport, freight, light commercial vehicle, Transport from knitting to dyeing	2,09	kg.km	Son of a Tailor
Transport, freight, light commercial vehicle, the dyeing to confectioning	13,68	kg.km	Son of a Tailor

Table 4.20: Input data for fabric knitting per functional unit (incl return rates).

4.11.4 Confectioning

Confectioning uses the same input as MTO, but 20% is added for overproduction and 30% is added for returns.

Process	Amount	Unit	Source
Electricity heat for production processes cutting, sewing, ironing, and heating.	0,39	kWh	Son of a Tailor
Water usage, washing process	0,23	Liter	Son of a Tailor
Electricity, Washing process	0,14	kWh	Son of a Tailor
Electricity, drying process	0,12	KWh	Son of a Tailor
Transport to washing facility	1,91	kg.km	Identified with Google maps

Table 4.21: Input data for confectioning processes and transport during the phase (incl return rates).

4.11.5 Production waste

Production waste is the same input as MTO, but 30% is added for returns.

Process	Amount	Unit	Source
Waste fabric to recycling per T-shirt	0,051	kg	Son of a Tailor (2023)

Table 4.22 Input data for production waste after the confectioning phase per functional unit (incl return rates).

4.11.6 Transport to distribution center

Transport to the distribution center is the same as in MTO but increased with 30% for return rates.

Process	Distance	Amount	Unit	Source
Freight, lorry 3.5-7.5 metric ton, EURO 6	from production to Airport, Portugal	12,44	kg.km	Identified by Google maps
Freight, aircraft, medium haul	From Airport -Aeroporto Sá Carneiro, Porto to Copenhagen Airport	679,72	kg.km	Identified by distance.to
Freight, lorry 3.5-7.5 metric ton, EURO 6	From Copenhagen Airport to Distribution center in Brøndby, Denmark	5,78	kg.km	Identified by Google maps

Table 4.23: Input data for transport to distribution center per functional unit (incl return rates).

4.11.7 Distribution

Distribution to customers is the same as in MTO but increased with 30% for return rates.

Process	Distance	Amount	Unit	Source
Freight, aircraft, medium haul	Transport to customers by airplane	1041,17	kg.km	Identified by distance.to
Freight, lorry 3.5-7.5 metric ton, EURO 6	Transport to customers by truck	45,33	kg.km	Identified by Google maps

Table 4.24: Input data for distribution per functional unit (incl return rates).

4.11.8 Use

Since the use phase is identical to MTO, the inputs are the same as described in inventory for the MTO system.

4.11.9 End-of-life of used T-shirt

The end-of-life of used T-shirts for the MP business model has been modelled with the same waste treatment scenario as the MTO business model. The only exception is the treatment of returned items which differs from the MTO business model, since the returned items end up at production or distribution site and not the customers. In a standard MP business model, there will be returns from customers.

In table 4.25, gives an overview of the selected sources and waste data for the end-of-life scenario for the MP business model.

Process	Amount	Unit	Source
Return rates	30	%	Invesp (2022)
Waste fabric	22,8	%	Son of a Tailor, Data from all production made in 2022
Deadstock	20	%	McKinsey & Global fashion agenda (2020)
Market oone Incineration rate	18,9	%	Cao et. al. (2022)
Market one Landfill rate	66,4	%	Cao et. al. (2022)
Market one Recycling rate	14,7	%	Cao et. al. (2022)
Market two Incineration rate	7	%	FOEE (2020)
Market two Landfill rate	31	%	FOEE (2020)
Market two Recycling rate	14	%	FOEE (2020)
Market three Incineration rate	25,53	%	Labfresh (2020)
Market three Landfill rate	57,45	%	Labfresh (2020)
Market three Recycling rate	10,64	%	Labfresh (2020)
Market four Incineration rate	55,93	%	Watson et. al. (2018)
Market four Landfill rate	38,15	%	Watson et. al. (2018)
Market four Recycling rate	0,43	%	Watson et. al. (2018)

Table 4.25: Sources on waste data for end–of–life.

4.11.10 End–of–life for returned items

The average return rate is around 30% (Saleh, 2022). The items can be resold or are discarded as waste. This needs to be accounted for in the LCA. Since, to our knowledge, there are no sources that state both return rates and how much of the returns are discarded, it is assumed that all return items will be waste treated with an equal distribution between recycling, landfill, and incineration. This is added in the modelling as extra production per T–shirt, and as extra waste in the end–of–life but is excluded in the use phase.

For the end–of–life of returned items in the MP business model, it has not been possible to find clear and concise data. The optimal data would be from a single reliable source stating both return rates and what is done with the returned items. The source should also provide good insight into a large percentage. But, as mentioned, this has not been possible to find. This is not surprising since there is a lack of transparency on this topic from the industry (Fashion Revolution, 2022). Due to the lack of data, it was decided to model the end–of–life of return rates in the MP with an even distribution between recycling, landfill, and incineration.

Process	Percentage %	Amount	Unit	Source
Recycling cotton	33	0,0148	kg	N/A
Landfill	33	0,0148	kg	N/A
Incineration	33	0,0148	Kg	N/A

Table 4.26: Input data for end-of-life for returned items per functional unit (only return rates)

4.11.11 End-of-life for deadstock T-shirt

As mentioned in section 3.2, in the MP system the end-of-life phase were split into three phases for better overview of the end-of-life for the T-shirt: End-of-life of used T-shirt, end-of-life of returned T-shirts and end-of-life of deadstock T-shirt. The end-of-life of deadstock T-shirt is what happens to the 20% over produced T-shirt in the MP system. As with the returned items it is assumed to be an equal split between recycling, landfill, and incineration. For overview see table 4.27:

Process	Percentage %	Amount	Unit	Source
Recycling cotton	33	0,0098	kg	N/A
Landfill	33	0,0098	kg	N/A
Incineration	33	0,0098	Kg	N/A

Table 4.27: Overview of distribution to processes in the End-of-life phase for deadstock

5 LIFE CYCLE IMPACT ASSESSMENT

In the following sections, the results of the LCA will be explored.

5.1 THE RESULTS

In the following, the results of the characterization methods of the four impact categories Global Warming Potential, Freshwater Ecotoxicity, Water Scarcity, and Land Use is presented. The results of the LCIA only reflects the data which has been collected in collaboration with Son of a Tailor in the given data period. The results are highly influenced by the chosen deadstock rate and the return rates for the MP business model. It is important to recognize that the results only relate to the goal and scope of this LCA, which is to investigate Son of a Tailor's benefits and the potentials of having a MTO business model over a MP business model, and what the baseline for a T-shirt in cradle to grave perspective is in the MTO business model. This is done by investigating the impact the two business models would have on production of a Supima cotton T-shirt. Thereby the results only reflect the specific T-shirt and no other types of apparel. See the overall results in table 5.1 and 5.2. It is further important to note that the results in table 5.1 and 5.2 are rounded off in scientific numbers. The percentages in differences between the different business models are calculated through the values in the results sheet in both the impact assessment and the interpretation.

The represented impact categories are expressed in various units. Global Warming Potential is quantified in kg CO_2e, which translates impacts into the equivalent emissions of Carbon dioxide. Water Scarcity is measured in m^3, representing the volume of depleted water. Freshwater Ecotoxicity is assessed using the unit kg 1,4-DCB, referencing the chemical compound 1,4-dichlorobenzene (DCB). Within the ReCiPe method, this compound serves as a reference for calculating potential harm from different substances, and the unit measures potential impact on combined concentrations of substance in air and water. Lastly, Land Use is quantified in square meters per crop equivalent (m^2 a crop eq), measuring the area of occupied land.

Life cycle phases	GWP for MTO [Kg CO2e]	GWP for MP [Kg CO2e]	Water Scarcity for MTO [m^3]	Water Scarcity for MP [m^3]
Total	3,35E+00	4,34E+00	1,27E−01	1,65E−01
Raw materials	1,07E+00	1,52E+00	8,76E−02	1,24E−01
Transport to production	2,29E−02	3,24E−02	2,54E−05	3,60E−05
Fabric knitting	3,73E−01	5,29E−01	1,65E−03	2,35E−03
Confectioning	1,55E−01	2,20E−01	9,80E−04	1,39E−03
Transport to distribution center	4,75E−01	5,84E−01	2,51E−04	3,09E−04
Distribution	7,34E−01	9,03E−01	4,07E−04	5,01E−04
Use	4,14E−01	4,14E−01	3,57E−02	3,57E−02
End−of−life	1,06E−01	1,06E−01	2,43E−05	2,43E−05
End−of−life only return rates	1,21E−03	2,27E−02	1,43E−06	1,09E−05
End−of−life of deadstock T−shirts	0,00E+00	1,49E−02	0,00E+00	7,17E−06

Table 5.1: Impact of MTO and MP in Global Warming Potential and Water Scarcity

Life cycle phases	Freshwater Ecotoxicity for MTO [kg 1,4 DCB]	Freshwater Ecotoxicity for MP [kg 1,4 DCB]	Land Use for MTO [m^2a crop eq]	Land Use For MP [m^2a crop eq]
Total	1,69E−01	2,27E−01	9,90E−01	1,39E+00
Raw materials	1,05E−01	1,48E−01	9,34E−01	1,32E+00
Transport to production	3,04E−04	4,32E−04	4,51E−04	6,40E−04
Fabric knitting	1,30E−02	1,85E−02	6,47E−03	9,19E−03
Confectioning	1,03E−03	1,46E−03	2,99E−03	4,25E−03
Transport to distribution center	1,24E−03	1,53E−03	6,79E−03	8,35E−03
Distribution	2,13E−03	2,62E−03	1,07E−02	1,31E−02
Use	3,34E−02	3,34E−02	2,88E−02	2,88E−02
End−of−life	1,29E−02	1,29E−02	1,88E.04	1,88E−04
End−of−life only return rates	5,95E−04	4,48E−03	64E−06	3,86E−05
End−of−life of deadstock T−shirts	0,00E+00	2,98E−03	0,00E+00	2,31E−05

Table 5.2: Impact of MTO and MP in Freshwater Ecotoxicity and Land Use

In order to understand the percentual difference between the MTO and MP model in the different impact categories, two types of calculation can be used. The first being with the MTO as baseline and calculating how much the MP model increases the environmental impact in relation to the MTO model. The second is with the MP as baseline and calculating how much the MTO decreases the environmental impact in relation to the MP model.

Both ways of calculating the percentual difference can be viewed in table 5.3 below.

Life cycle phases	Freshwater Ecotoxicity	Land Use	Global Warming potential	Water scarcity
MTO as baseline (cradle to grave)	33,97 %	40,36 %	29,66 %	30,01 %
MTO as baseline (raw materials to confectioning)	41,91 %	41,91 %	41,91 %	41,91 %
MTO as baseline (raw materials to distribution)	41,39 %	41,57%	33,83 %	41,77 %
MP as baseline (cradle to grave)	25,36 %	28,75 %	22,88 %	23,08 %
MP as baseline (raw materials to confectioning)	29,53 %	29,53 %	29,53 %	29,53 %
MP as baseline (raw materials to distribution)	29,27 %	29,36 %	25,28 %	29,47 %

Table 5.3 The difference in percentages between MTO and MP model with different baseline

The following section and the interpretation will use the first way of calculating the percentual difference, where the MTO model is the baseline for calculation.

5.1.1 Impact on Global Warming Potential

Global Warming Potential (kg CO_2e) describes the product's contribution to global warming. The total Global Warming Potential for the MTO business model in a cradle to grave perspective is **3,35kg CO_2e**, while the Global Warming Potential for the MP model in a cradle to grave perspective is **4,34kg CO_2e**. This means that the MP system has **29,66%** larger GWP impact than the MTO system.

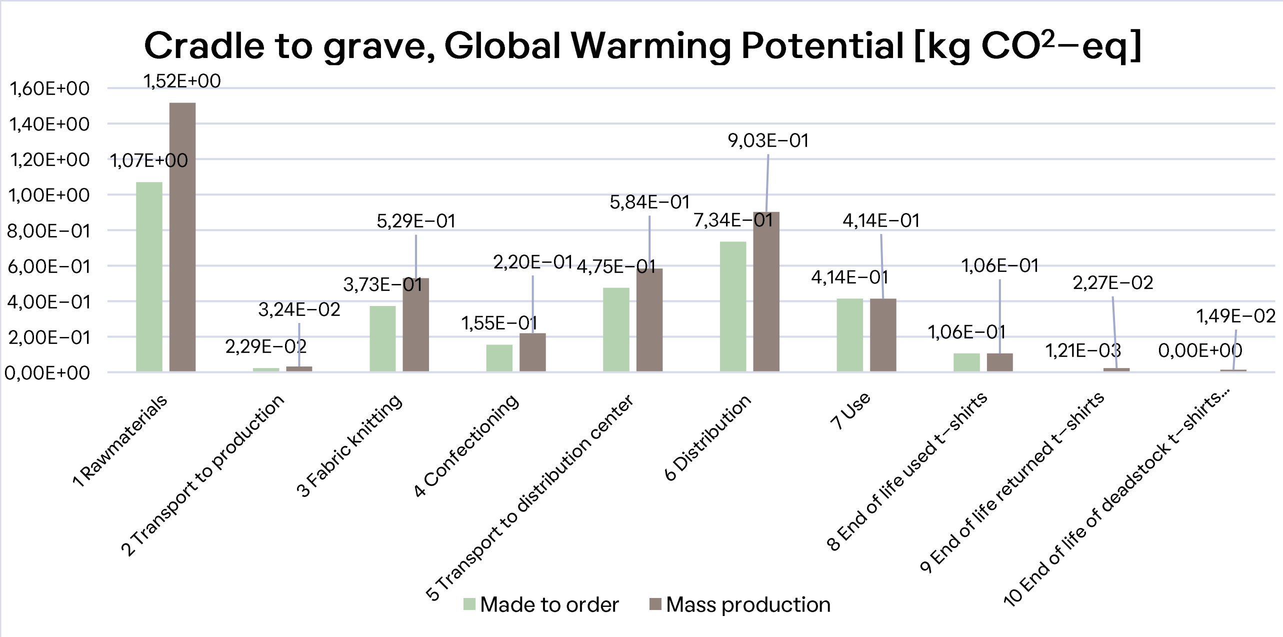

Figure 5.1: Global Warming Potential, cradle–to–grave.

For the MTO business model the biggest contributor to GWP is Raw materials with **1,07 kg CO_2e**. The second largest contributor is Distribution with **0,73 kg CO_2e**, and the third largest is Transport to distribution center with **0,47 kg CO_2e**.

For the MP model, the biggest contributor is also Raw materials with **1,52 kg CO_2e**. The second largest contributor is Distribution with **0,90 kg CO_2e**, and the third largest is Transport to distribution with **0,58 kg CO_2e**.

Since use and end–of–life are modelled only on generic and secondary data. The Global Warming Potential impact has also been examined in two cradle–to–gate scenarios: Raw materials to confectioning and Raw materials to distribution.

5.1.2 Impact on Freshwater Ecotoxicity

The results of Ecotoxicity, freshwater (kg 1,4–DCB), describe toxins introduced into freshwater that can be destructive to the ecosystem.

For MTO the total impact on Freshwater Ecotoxicity is **0,17kg 1,4 DCB**. The MP system has a **33,97%** higher impact than the MTO system with a total impact of **0,23 kg 1,4 DCB**.

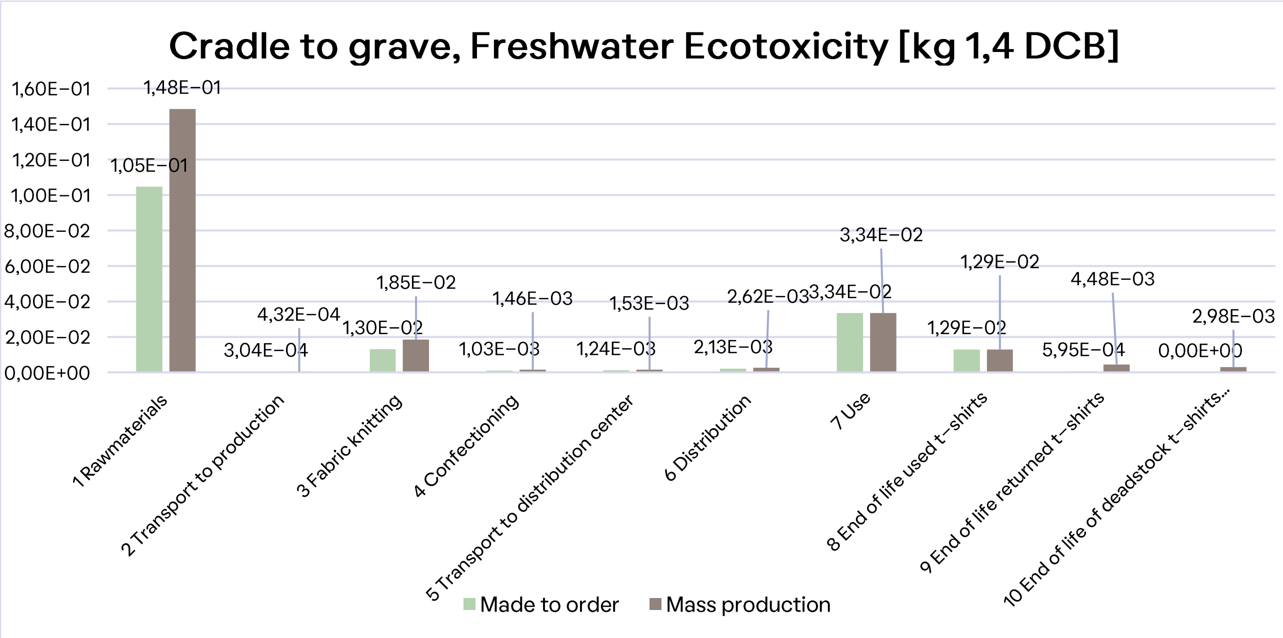

Figure 5.4: Freshwater Ecotoxicity cradle-to-grave

As displayed on the graph, the biggest contribution to Ecotoxicity comes from the raw materials phase in both the MTO business model and the MP business model. For MTO, the Raw material impact is **0,10kg 1,4-DCB**, and for MP it is **0,15 kg 1,4-DCB**. The second biggest contribution is from the use phase, where both MTO and MP have an impact of **0,03 kg 1,4 DCB**. The third biggest contribution is from fabric knitting, where MTO has an impact of **0,01 kg 1,4-DCB**, and MP has an impact of **0,02 kg 1,4 DCB**.

5.1.3 Impact on Water Scarcity

The results of water use (m^3 world eq.) describe how much water is used relative to how much water is available in a given area. This does not relate to water consumption, but instead to how much a product is influencing the scarcity of water. The total Water Scarcity impact for MTO is **0,13 m^3**. For MP it is **0,17 m^3**, which is a **30,01%** increase from the MTO to the MP business model.

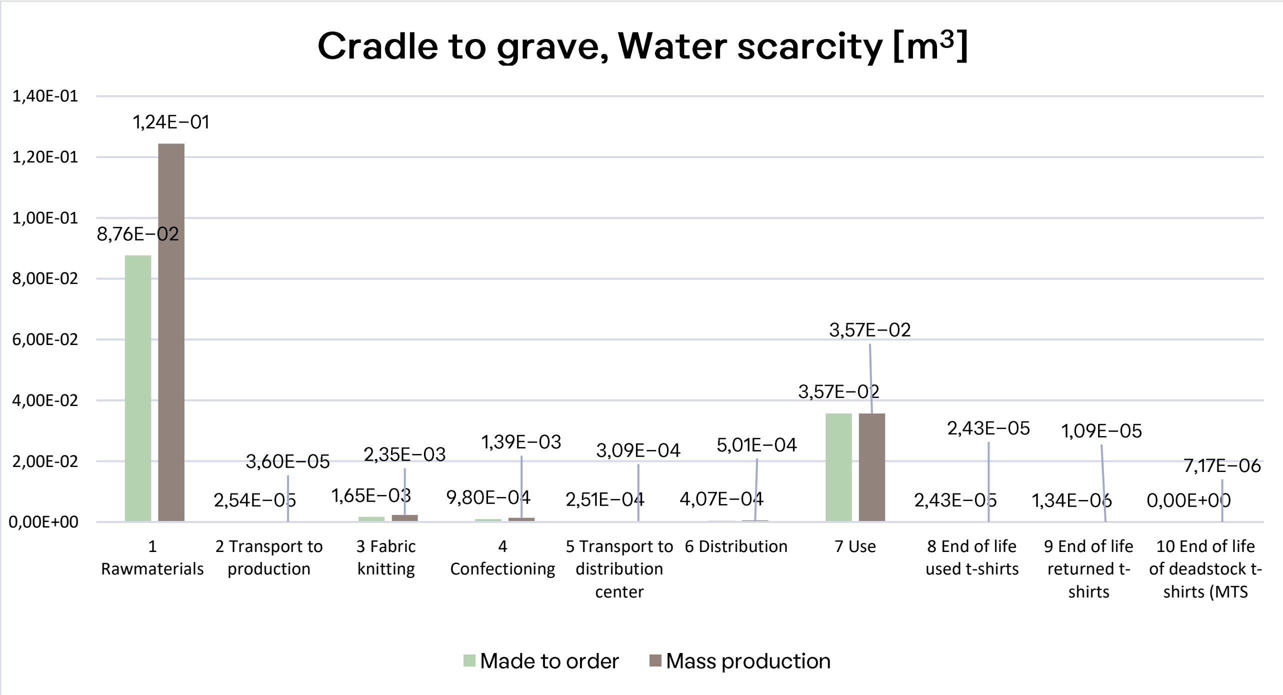

Figure 5.7: Water Scarcity, cradle-to-grave

As displayed in the graph the biggest contributor to MTO is raw materials with an impact of **0,09 m**^{3}. The same is true for the MP model, which has an impact of **0,12 m**^{3} in raw materials.

The second largest contributor is the use phase, where both MTO and MP have an impact of **0,04 m**^{3}. The rest of the impacts are relatively low.

6 LIFE CYCLE INTERPRETATION

The interpretation section of this LCA will investigate the results from the impact assessment in order to conclude what the results mean, and what they say about Son of a Tailor's MTO business model and the baseline of the T–shirt, as well as the difference between the MTO system and the MP system. In this regard, it is important to acknowledge the capabilities and limitations of the LCA method. Some of these perspectives will be reflected below.

First, an LCA assesses the potential environmental effects of products or systems, not the real or actual effects. An LCA is a scientific model of reality and not a direct representation of reality, which leads to uncertainties in the results. LCA is a useful method for identifying which phase in a product's life cycle contributes the most to its environmental impact. It is important to note that an LCA provides a static picture rather than a dynamic one, and results should be viewed in that context. LCAs cannot encompass all factors and data due to the complexity of reality. This is why system boundaries are established to define what is included and excluded in the study. Additionally, an LCA solely focuses on environmental factors and does not consider economic or social aspects. There are numerous ways to impact the environment, and the LCA method is limited to the available calculation methods for assessing these impacts.

The LCA results clearly highlight that the raw material extraction phase has the greatest influence across all four impact categories. In the Global Warming Potential impact category, the fabric knitting and the two transportation phases to the customers are also contributing with a reasonable amount. These four phases are responsible for 79% of the impact in the Global Warming Potential for the MTO system, and 81% for the MP system. In the Water Scarcity impact category, for both the MP and MTO system, raw materials exert the largest impact. Following this, the use phase and fabric knitting has the second and third most significant contributions to Water Scarcity. In the Freshwater Ecotoxicity impact category, fabric knitting, the end–of–life phase of used T–shirts, and the use phase stand out as significant contributors. Among these, the use phase comes in second place after raw materials as the most influential contributor across all the impact categories. Examining the Land Use category, it becomes evident that only raw materials make a significant contribution, with no other impact category showing notable involvement. In the next section, we will delve into the LCA phases to gain a more comprehensive understanding of the processes driving this contribution and the underlying reasons.

6.1 INTERPRETATION OF THE RESULTS

6.1.1 Investigating life cycle phases

6.1.1.1 Raw materials contributing processes

To understand why the raw material phase is the largest contributor, an analysis of this phase has been conducted on all four impact categories. This can be seen in the graphs below:

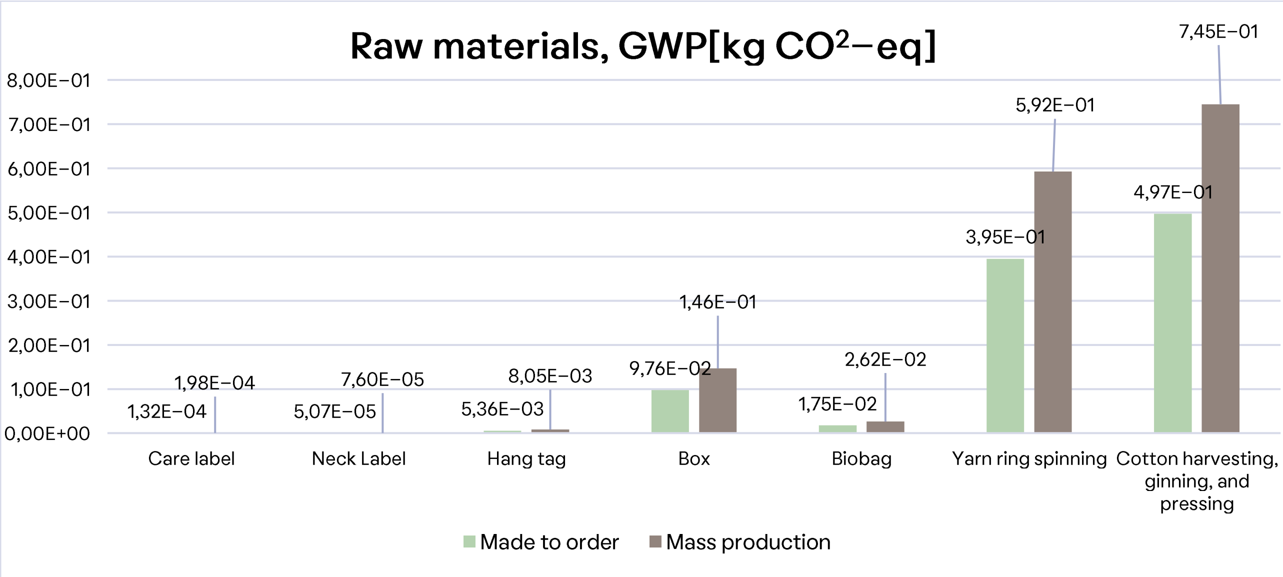

Figure 6.1: Global Warming Potential, raw materials.

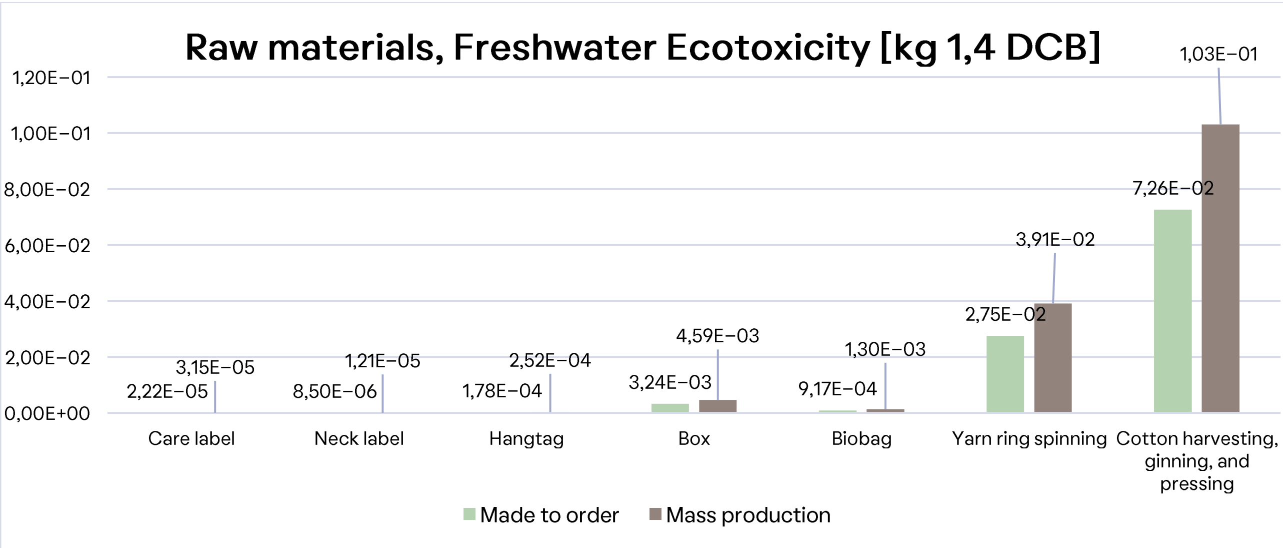

Figure 6.2: Freshwater Ecotoxicity, raw materials.

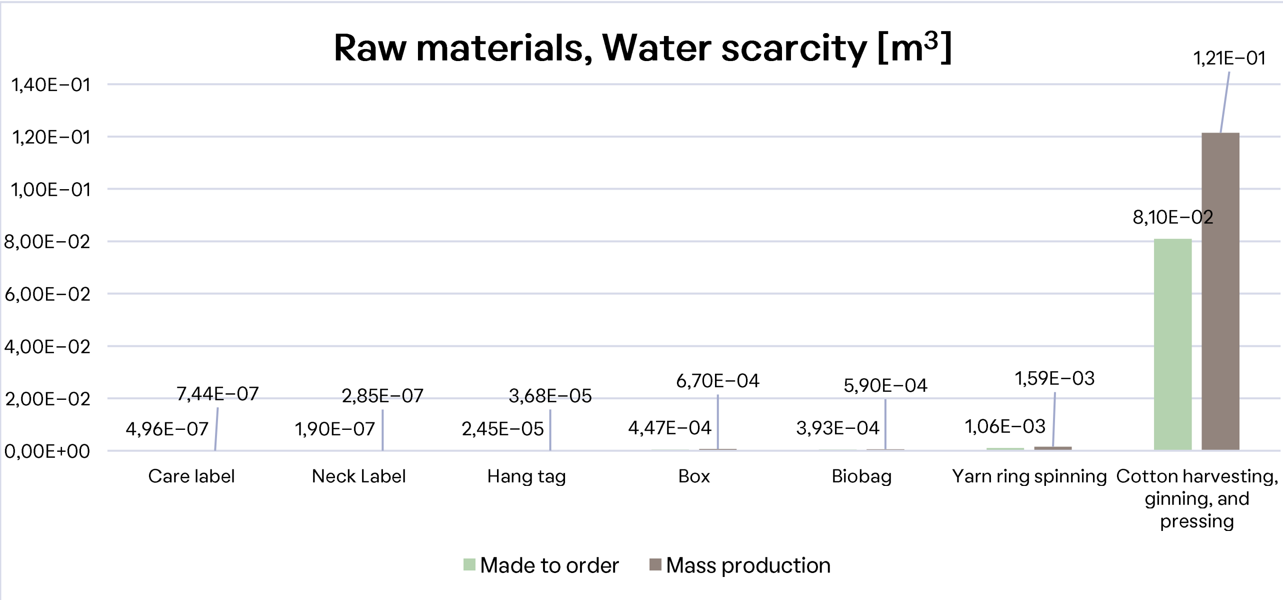

Figure 6.3: Water Scarcity, raw materials.

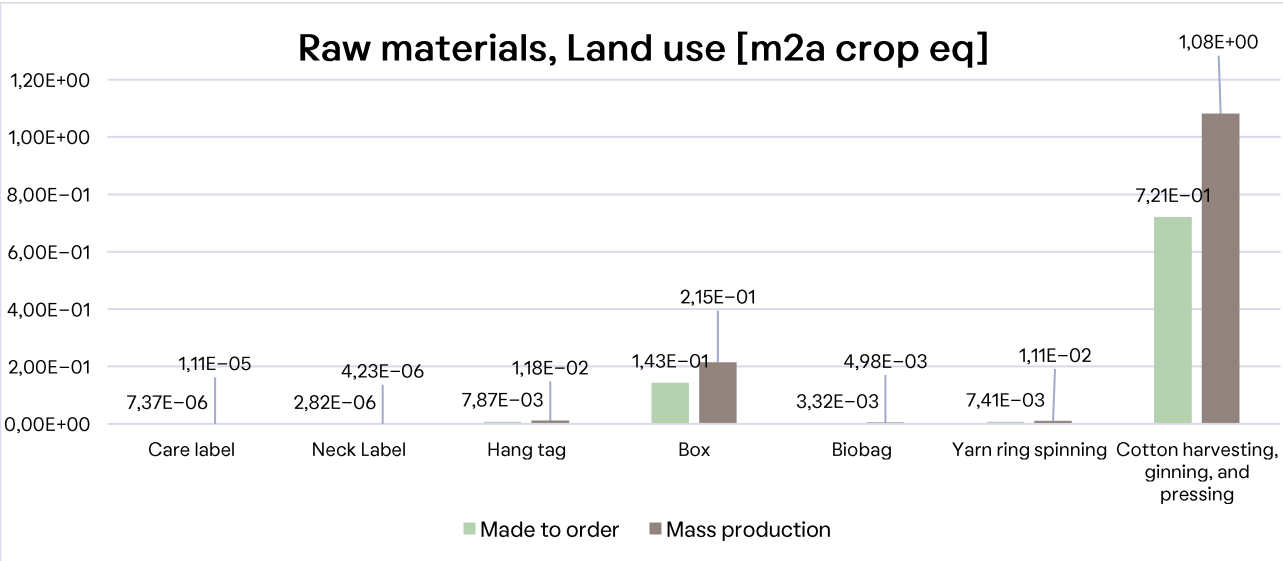

Figure 6.4: Land Use, raw materials.

In the Global Warming Potential, the most influential processes are yarn ring spinning, as well as cotton harvesting, ginning, and pressing. Additionally, the impact of the cardboard box used for packaging the T–shirt, has a relatively noticeable. The significant impact of yarn ring spinning predominantly stems from the substantial consumption of electricity and natural gas used in this process. As for cotton harvesting, ginning, and pressing, the noticeable contribution arises from the emission of CO_2 throughout the growing and harvesting phases, along with the use of tillage ploughs during cotton seed harvesting.

The impact of the cardboard box is also noteworthy due to its composition as a wood–derived material. Conversely, the biobag made from PLA exerts a relatively minor influence, primarily due to its relatively small contribution to the overall T–shirt production weight.

In the Water Scarcity impact category, the cotton harvesting, ginning, and pressing process is the main contributor. This is due the amount of water used in growing cotton seeds.

In the Freshwater Ecotoxicity yarn ring spinning, as well as cotton harvesting, ginning, and pressing, are the two most contributing processes. For the cotton harvesting, ginning, and pressing, the high impact is caused by fertilizers used to grow the cotton seeds. In yarn ring spinning, the high impact stems from consumption and distribution of electricity. The impact from electricity stems from the release of toxic material into fresh water due to the use of copper for the construction of electricity grids and networks.

In the Land Use impact category, the significant contributors once more include the process of cotton harvesting, ginning, and pressing, as well as the process for the cardboard box. The contribution of the cardboard box stems from its composition as a biomaterial derived from forested wood, necessitating land resources for its production. Notably, the production of cotton seeds also requires substantial amounts of land. The production of cotton seeds is a sub process to cotton harvesting, ginning, and pressing and is the reason for significant impact of the process.

6.1.1.2 Transport to production contributing processes

In this section the processes contributing to transport to production are examined. In the graphs below, the impact in the four different impact categories is shown for this process.

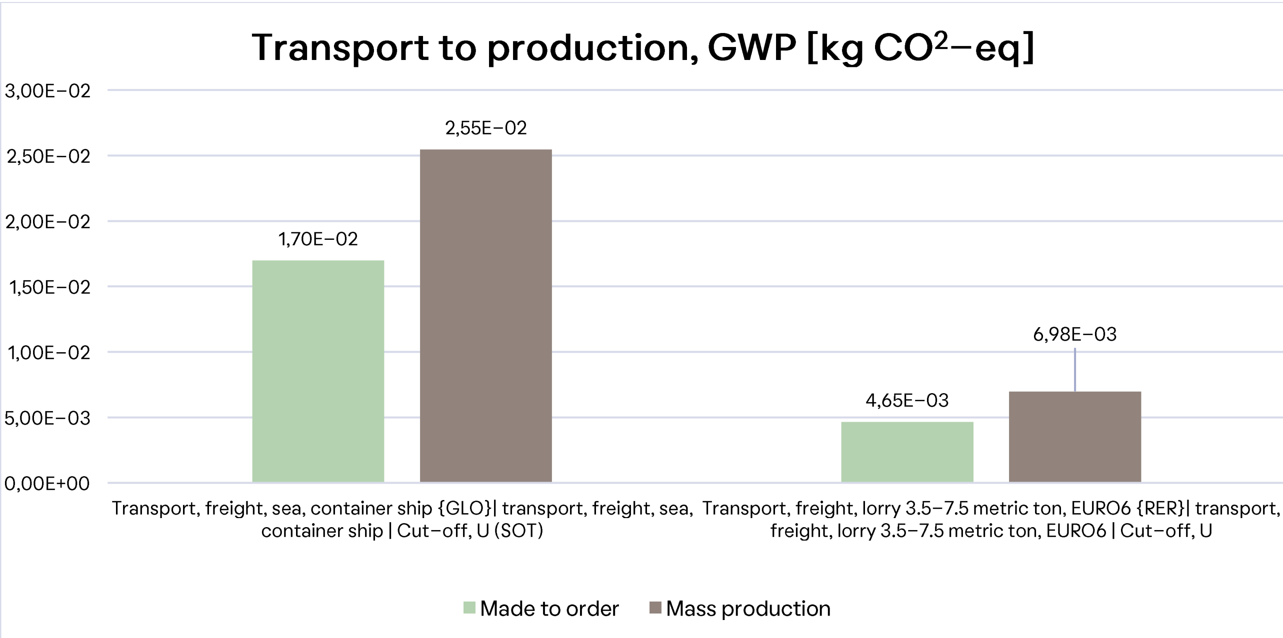

Figure 6.6: Global Warming Potential, transport to production.

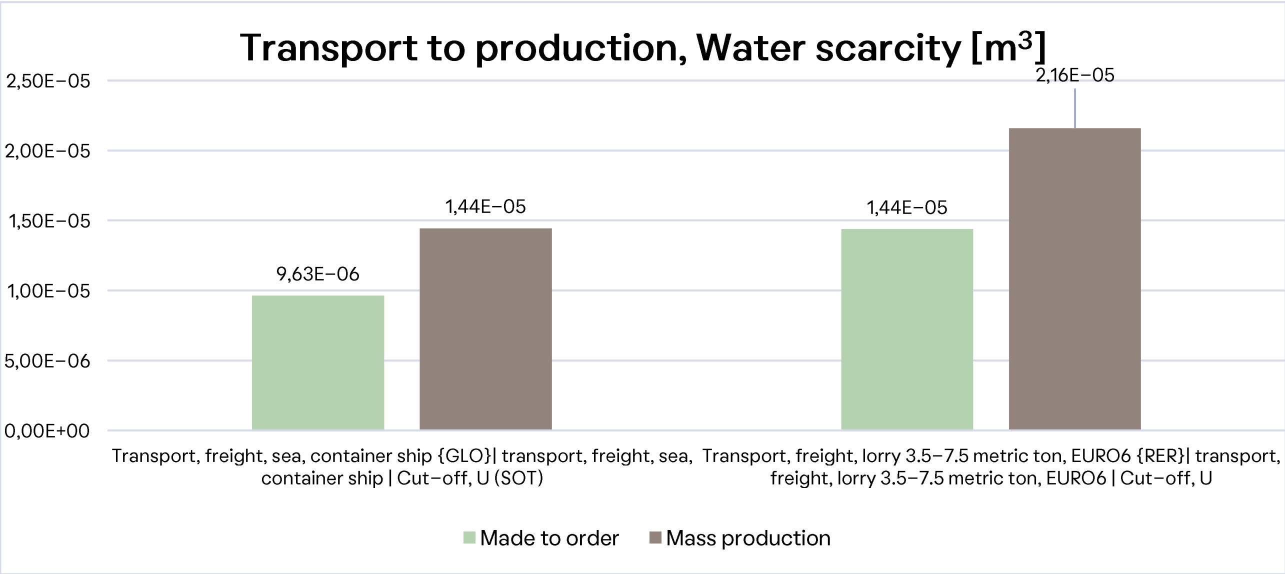

Figure 6.7: Water Scarcity, transport to production.

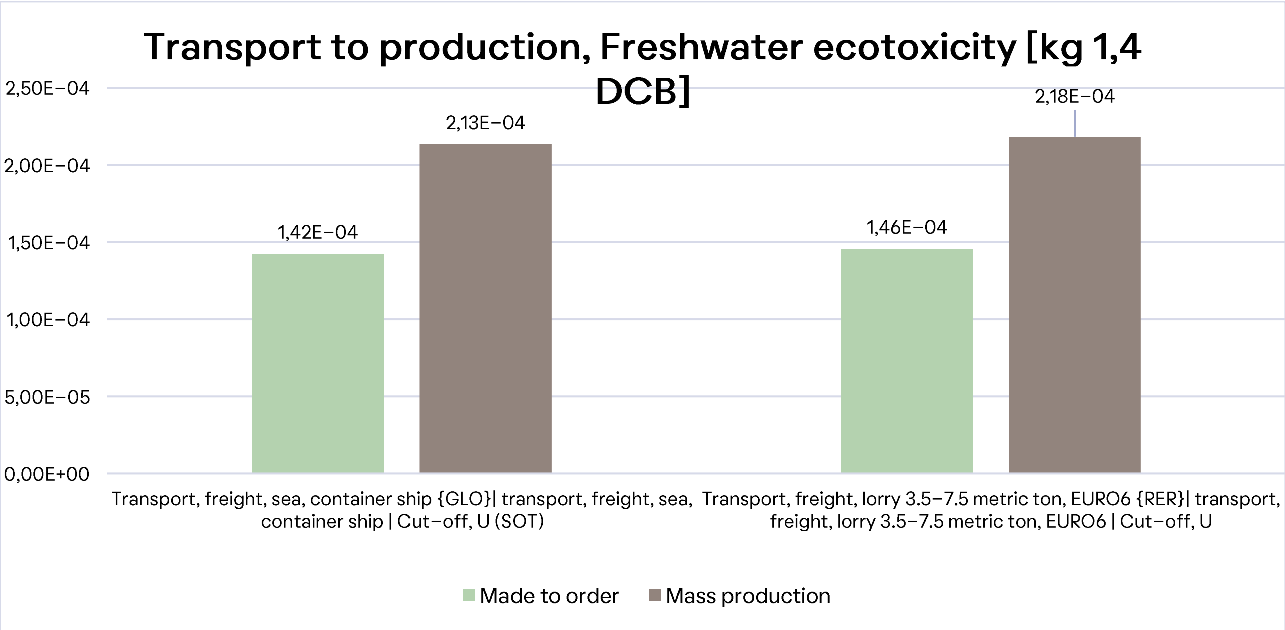

Figure 6.8: Freshwater Ecotoxicity, transport to production.

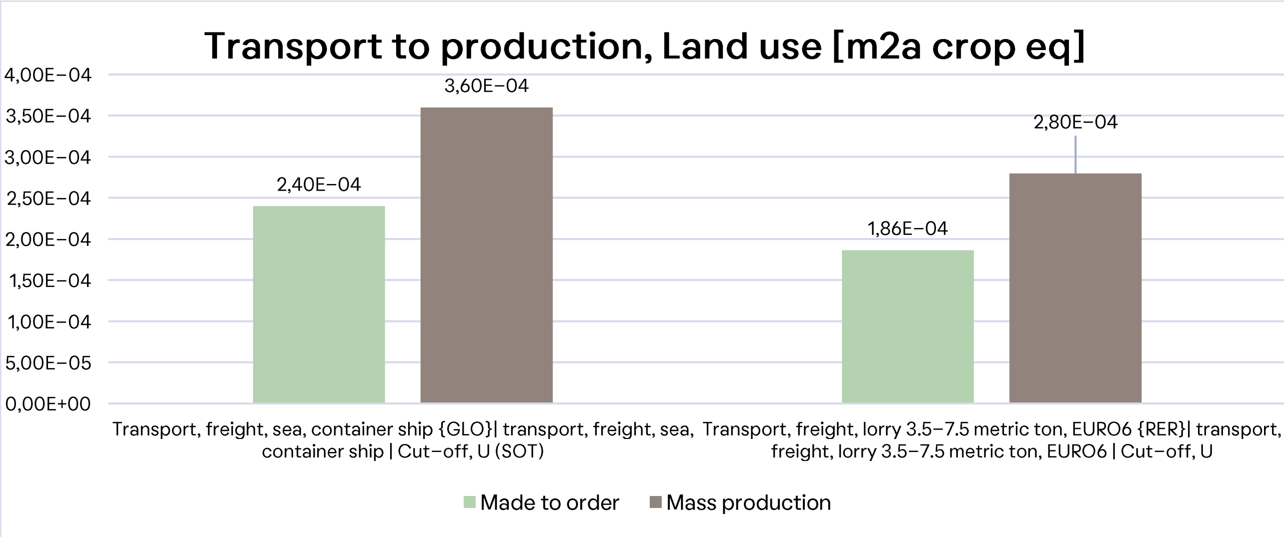

Figure 6.9: Land Use, transport to production

In the Global Warming Potential category, for the transportation to production, there are only two processes: Freight with container ship and freight with lorry truck. The transport by container ship contributes the most due to the longer distance travelled with that mode of transport.

In the Water Scarcity category, the transportation by lorry truck is contributing more due to a higher use of diesel per km, and diesel production itself contributes to this impact category.

In the Freshwater Ecotoxicity category, transportation by lorry truck is also the biggest contributor, but it is almost equal to the process for transport by container ship.

In the Land Use category, the contributing part for the lorry truck is road construction and for the container ship it is the production of heavy fuel oil.

6.1.1.3 Fabric knitting contributing processes

In this section, the processes contributing to fabric knitting will be examined. In the graphs below contributions for the four impact categories are shown.

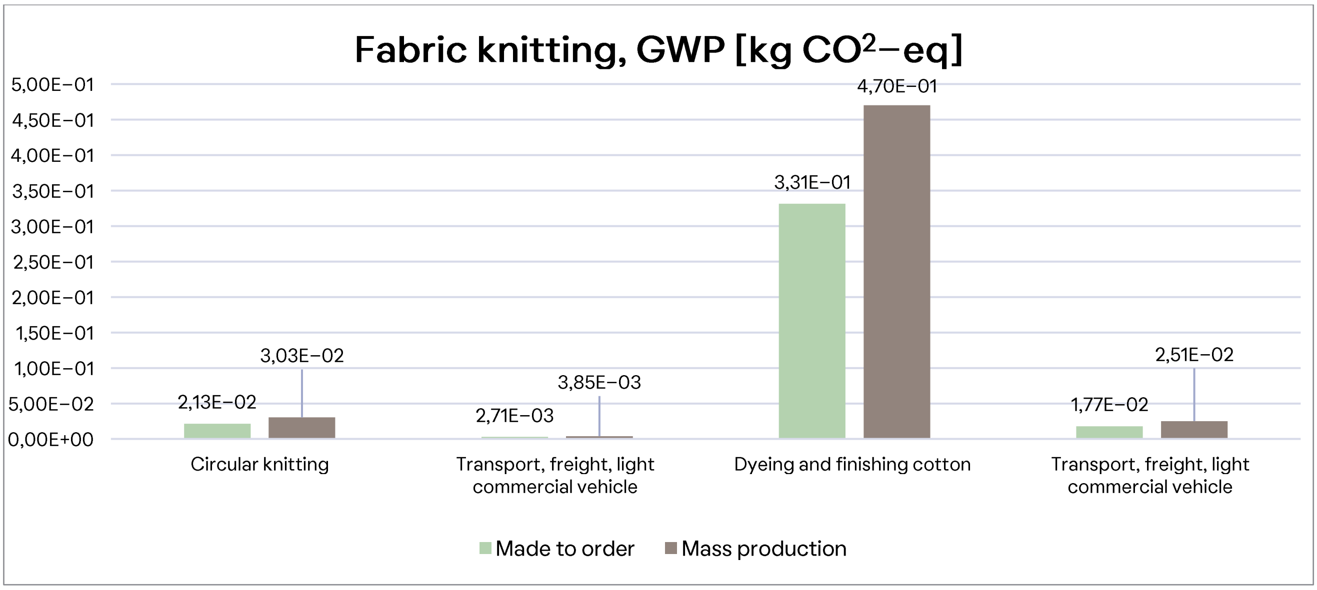

Figure 6.10: Global Warming Potential, Fabric knitting

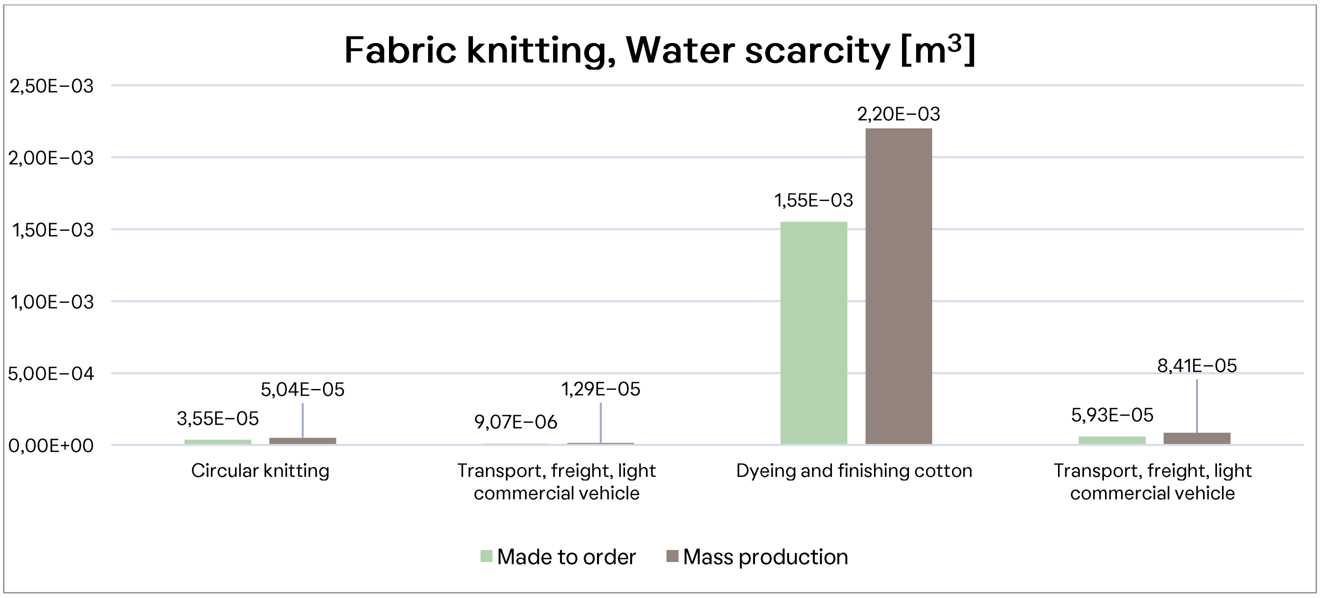

Figure 6.11: Water Scarcity, Fabric knitting

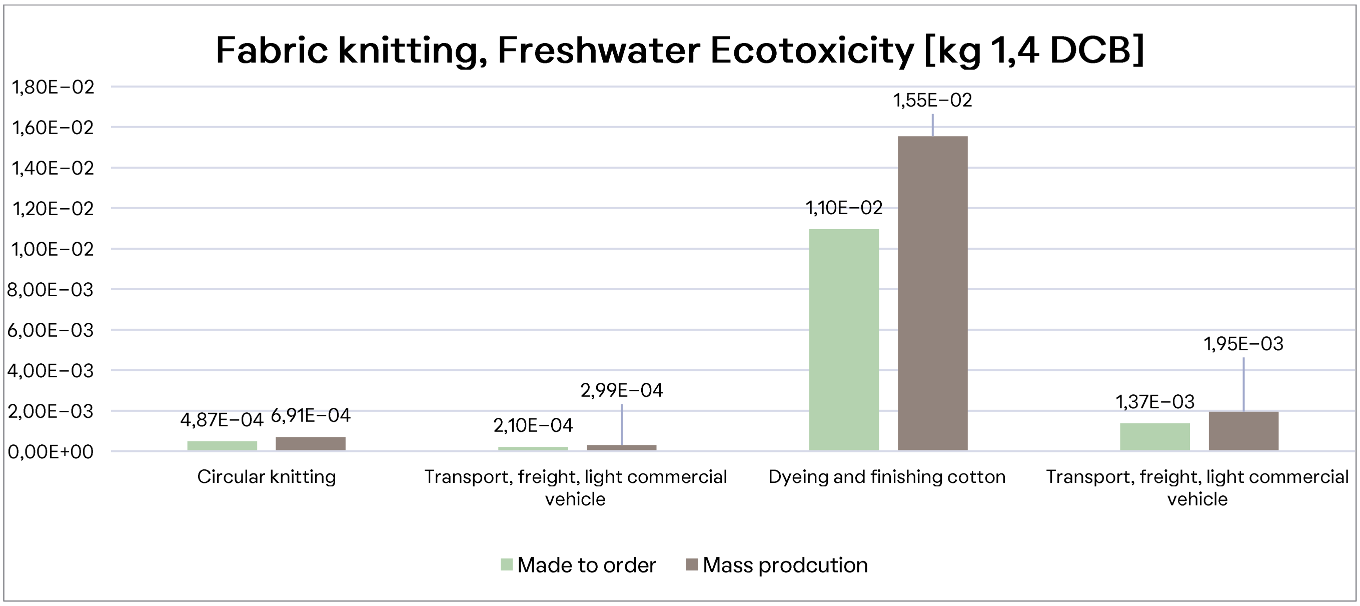

Figure 6.12: Freshwater eco toxicity, Fabric knitting

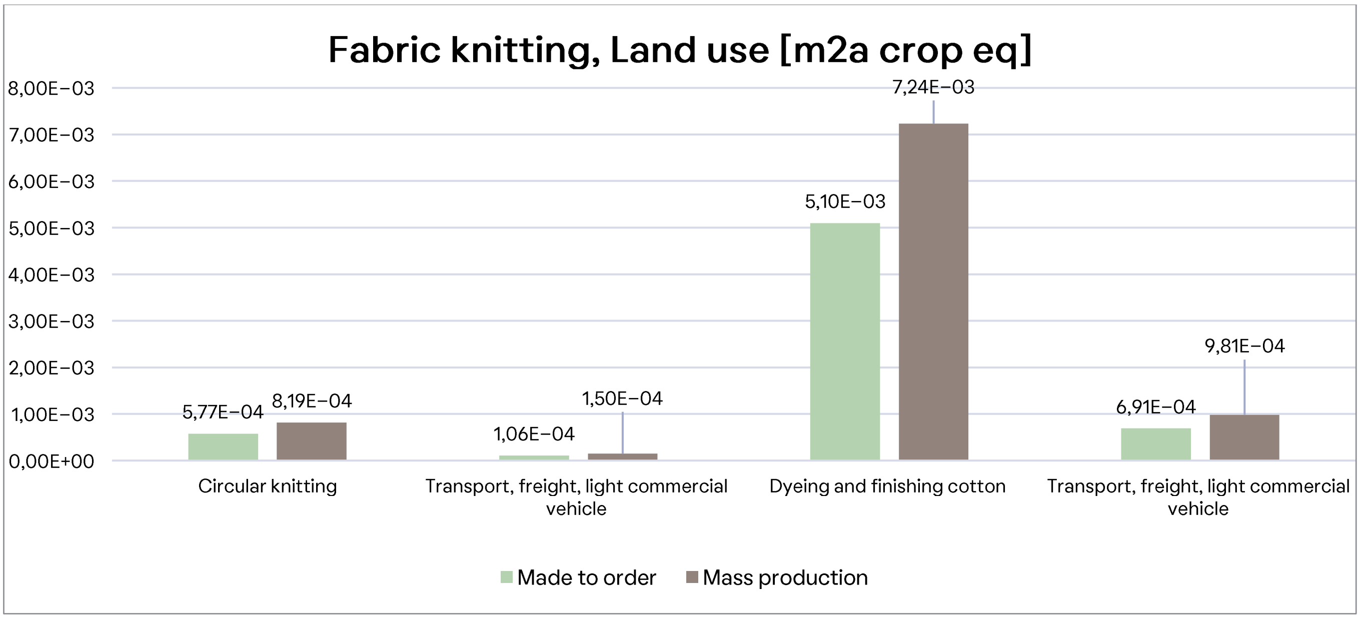

Figure 6.13: Land Use, Fabric knitting

In all four impact categories for the fabric knitting phase, dyeing, and finishing of the cotton has the highest impact. Relative to the dyeing and finishing process, the other processes have almost no impact. In fact, the dyeing and finishing contributes to 89 % of the Global Warming Potential, which is why we will not go further into the other processes, and instead focus on the dyeing and finishing.

6.1.1.4 Confectioning contributing processes

In this section, the contributing processes to the confection process will be unfolded. Graphs for the four different impact categories can be seen below.

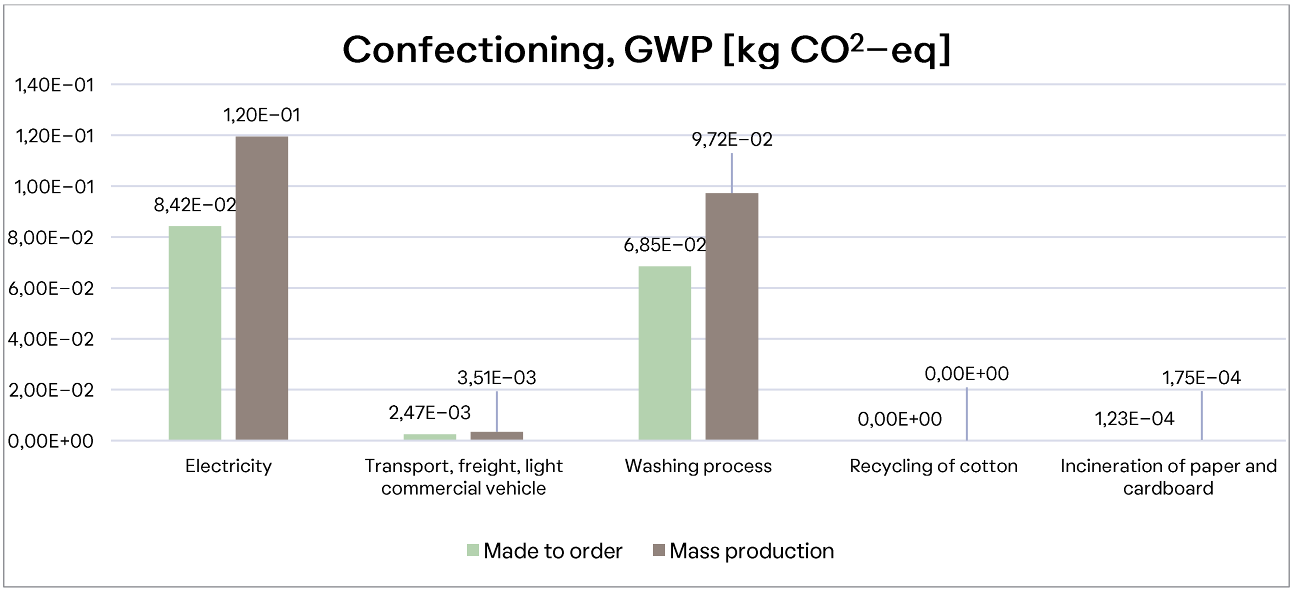

Figure 6.14: Global Warming Potential, confectioning.

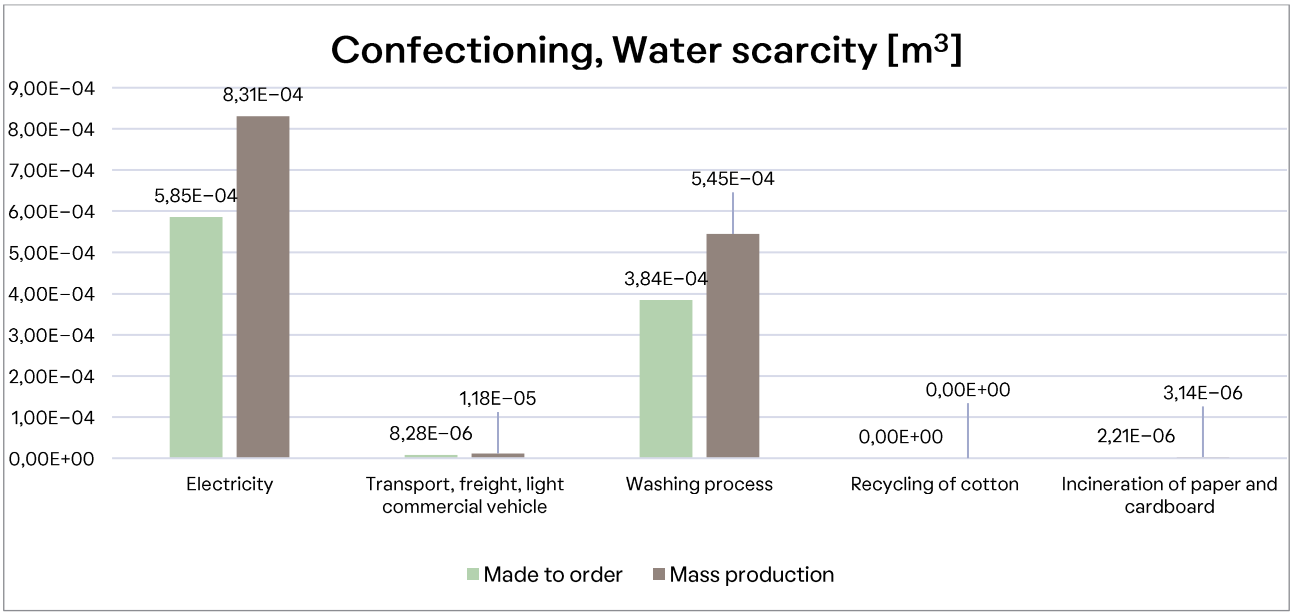

Figure 6.15: Water Scarcity, confectioning

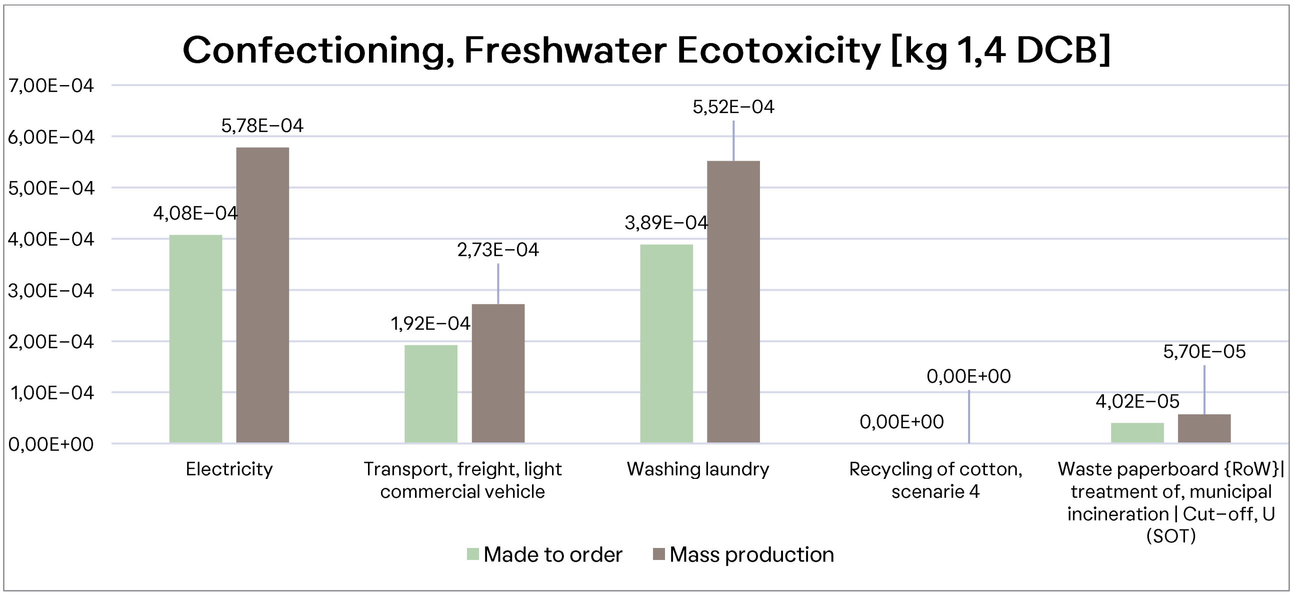

Figure 6.16: Freshwater eco toxicity, confectioning

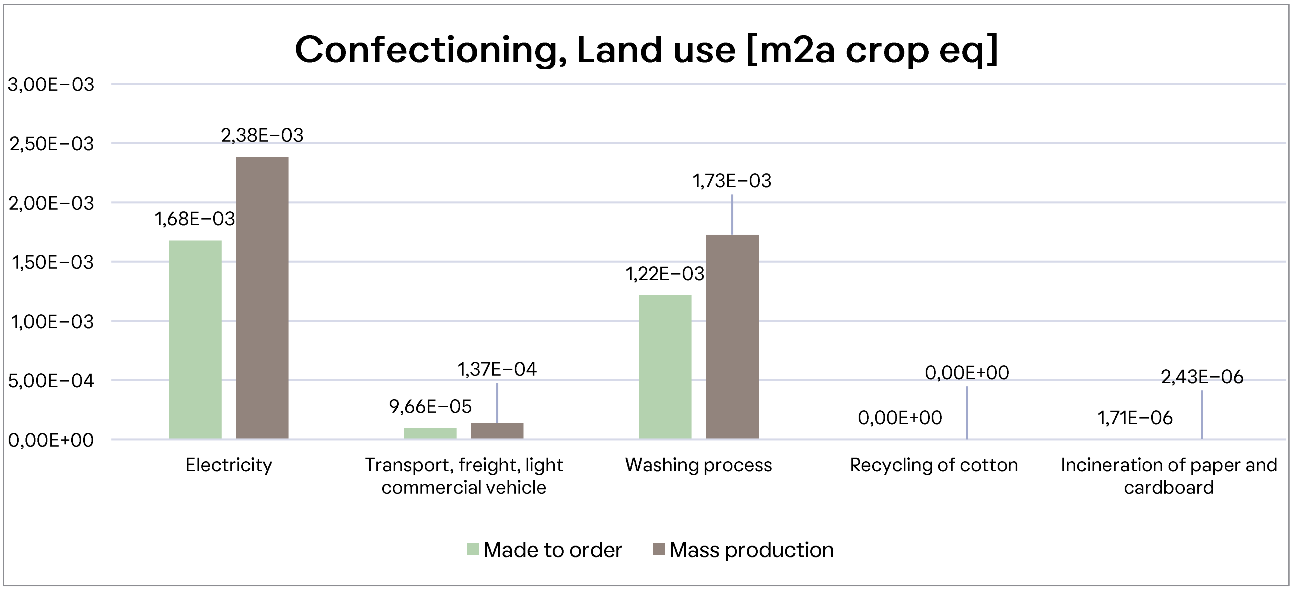

Figure 6.17: Land Use, confectioning

In the Global Warming Potential, the consumption of electricity in the confectioning phase is the highest contributor. This is caused by the processes in the electricity mix that are used in the modelling, as well as the consumption of electricity during production. The process for washing laundry also has a relatively high contribution. This is due to consumption of both electricity and natural gas in that process.

In the Water Scarcity the highest contributors are the consumption of electricity as well as the washing laundry process. The contribution from the electricity process stems from electricity produced by hydro power as well as the use of natural gas. The laundry washing process has a large contribution due to the consumption of water in the process.

In the Freshwater Ecotoxicity category, the laundry washing process has the largest contribution due to the wastewater emissions in the process.

In the Land Use category, electricity has the largest impact due to heat and power co–generation, where different wood materials are used to create energy. Wood materials are forested, and therefore has a large land use. The second largest contribution stems from washing laundry, wherefrom it is the consumption of electricity that is the cause of the impact, since the energy mix for washing laundry also uses co–generation with wood materials.

Overall, the confectioning phase does not have a large impact on the T–shirts life cycle.

6.1.1.5 Transport to distribution center process contribution

Before being distributed to the customers, the T–shirt arrives at a distribution center. In this section, the contribution of the process of transport between production and distribution center will be explored. Graphs for the four different impact categories can be seen below.

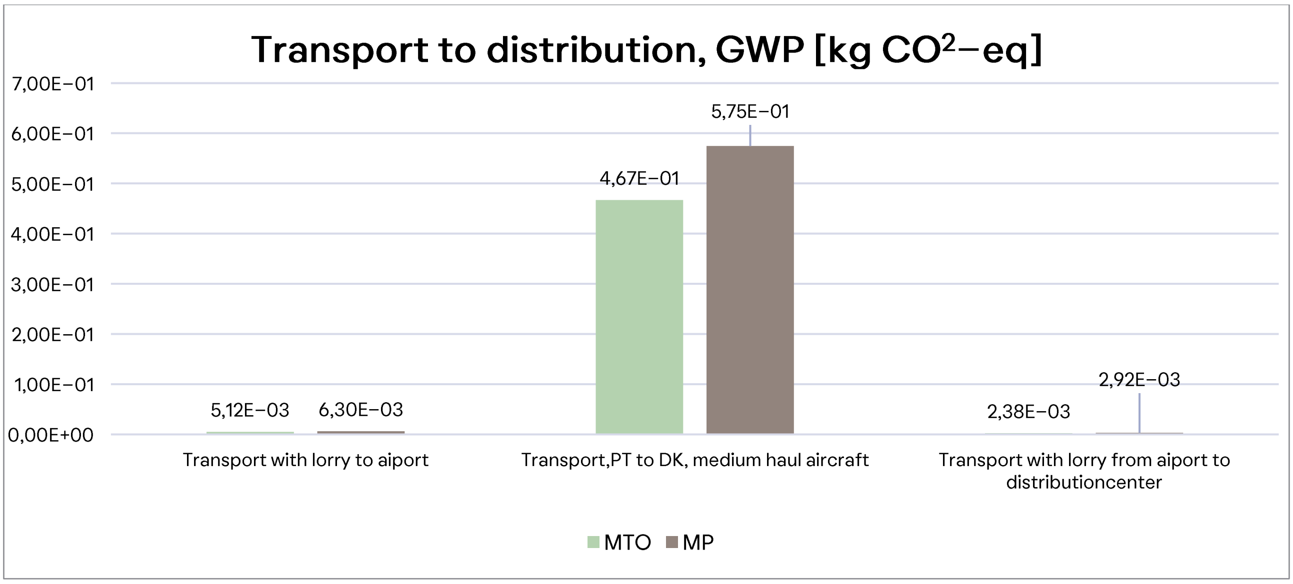

Figure 6.18: Global Warming Potential, Transport to distribution center

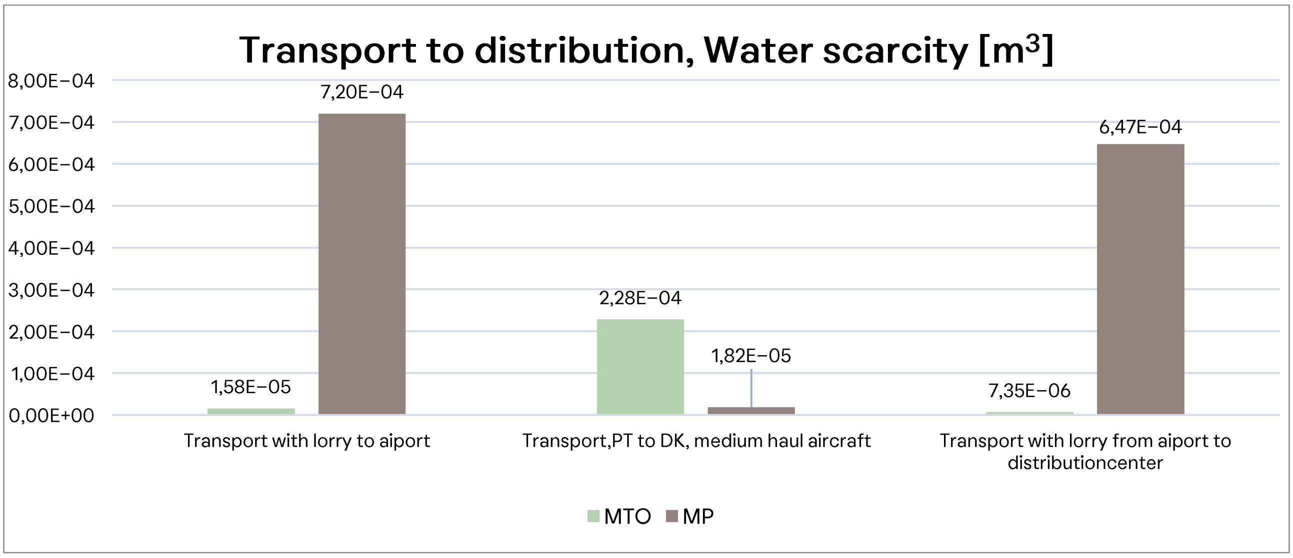

Figure 6.19: Water Scarcity, Transport to distribution center

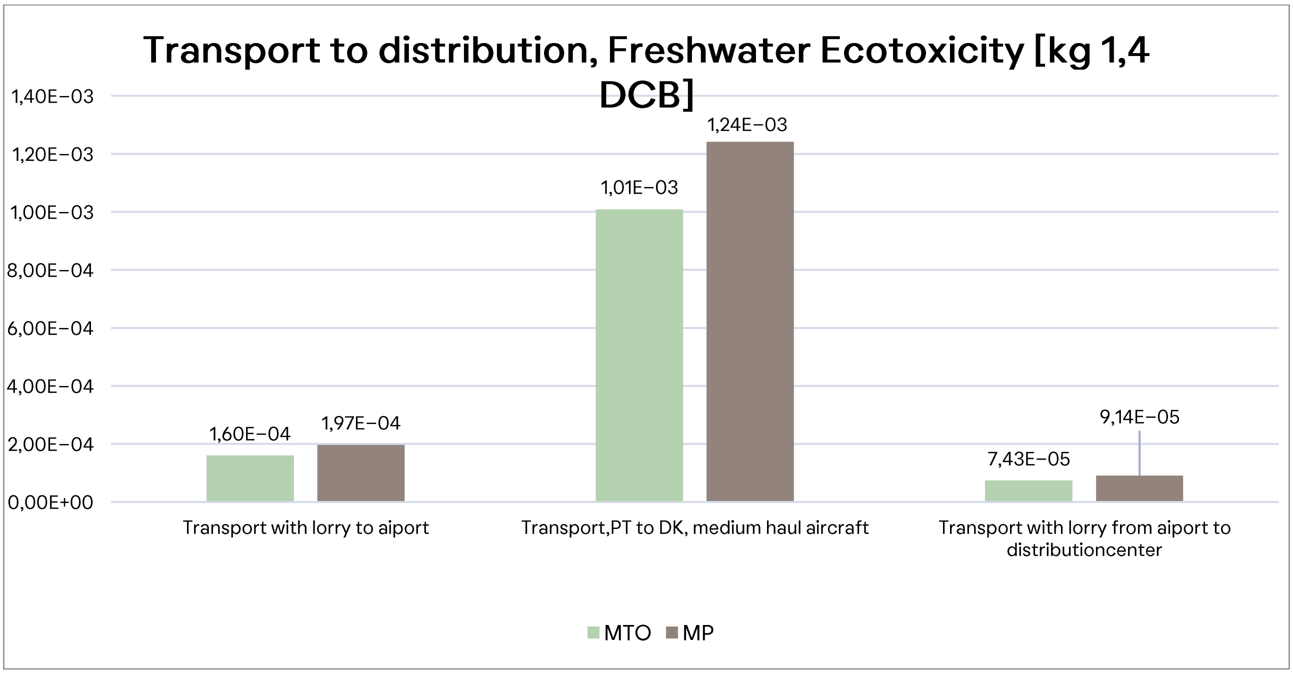

Figure 6.20: Freshwater Ecotoxicity, Transport to distribution center

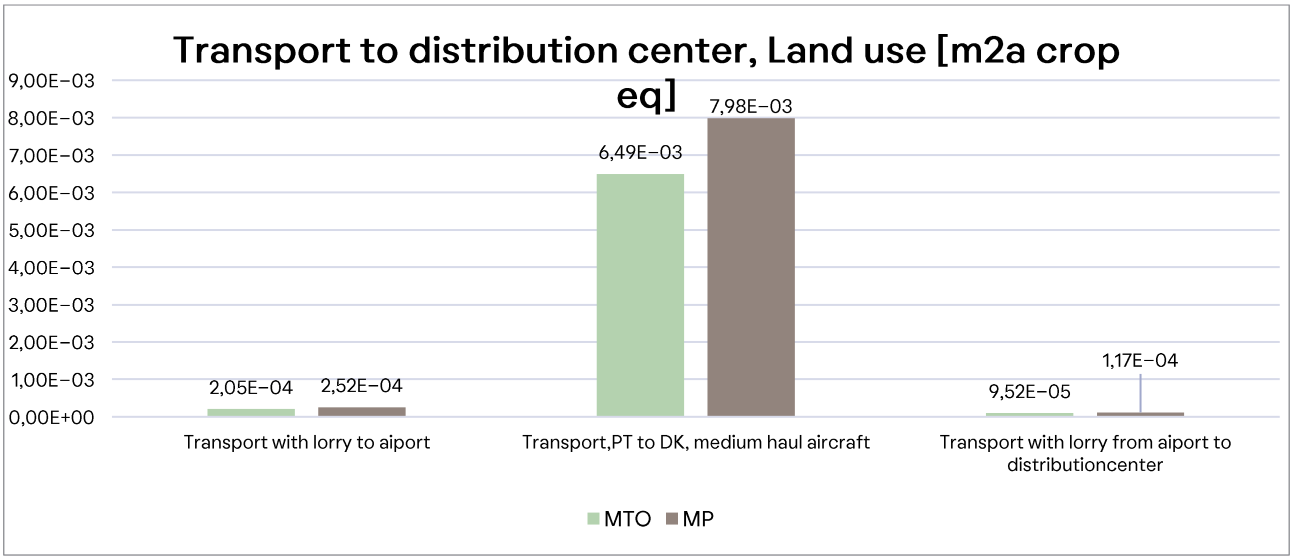

Figure 6.21: Land Use, Transport to distribution center

In all four impact categories, transport by aircraft is by far the most contributing factor in the transport to distribution center phase. This is due to the distance travelled by aircraft, which is at large caused by emissions during flight and the construction of the aircraft.

6.1.1.6 Distribution process contribution

After arriving at the distribution center, the T–shirt is distributed to the customers. This section will explore which processes are contributing the most to the distribution phase. Graphs for the four impact categories can be seen below.

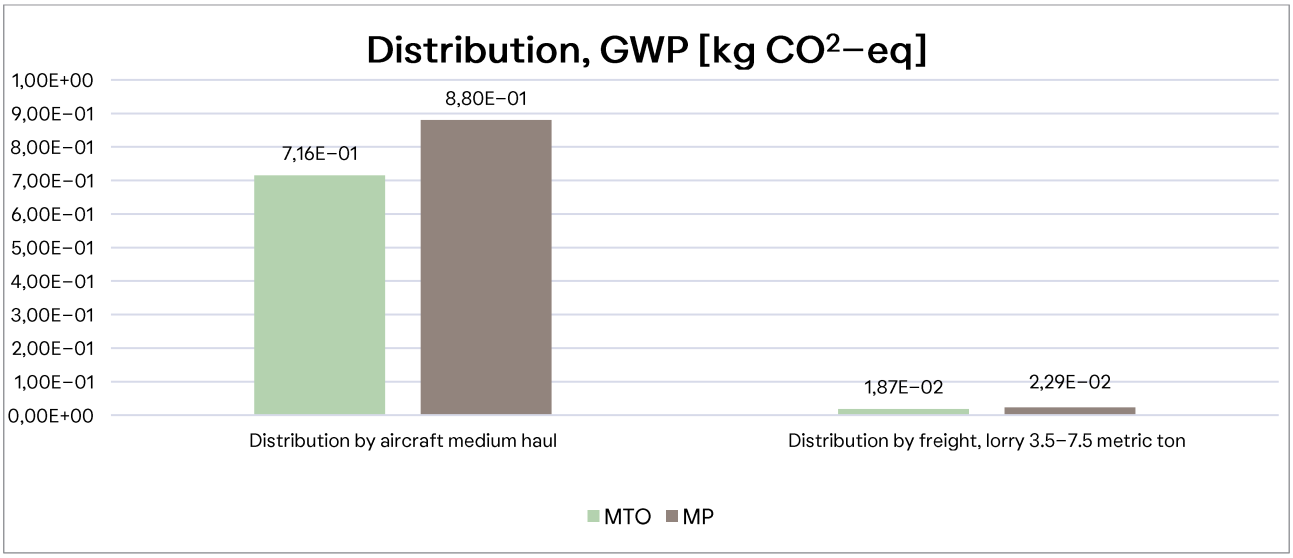

Figure 6.22: Global Warming Potential, distribution

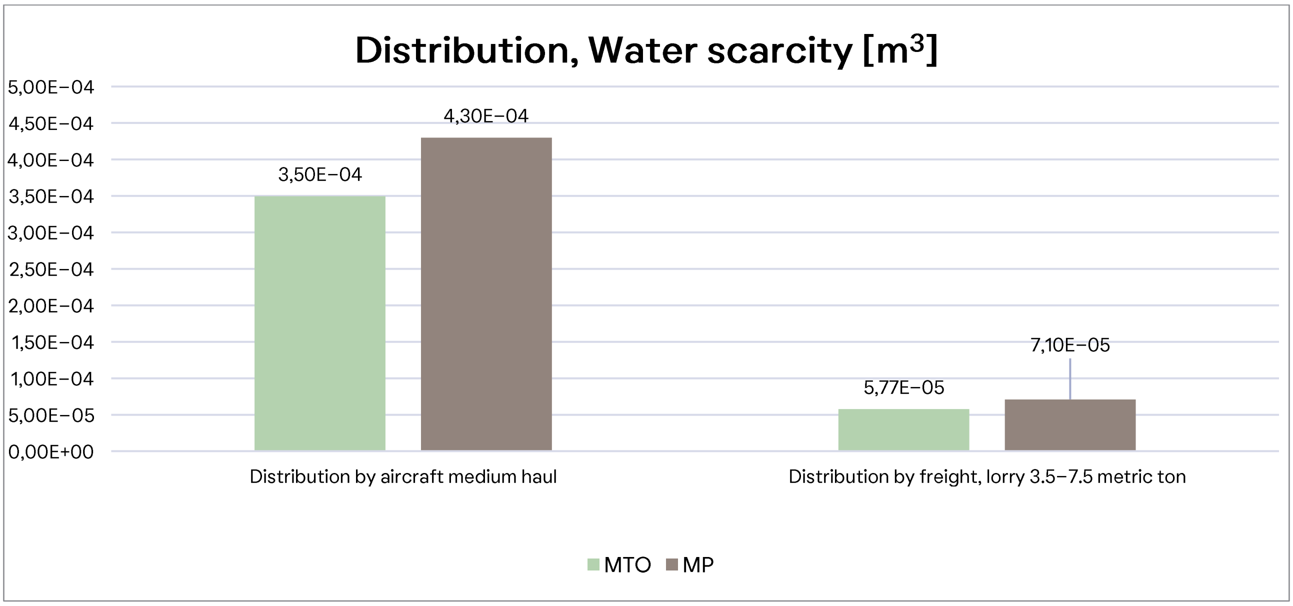

Figure 6.23: Water Scarcity, distribution

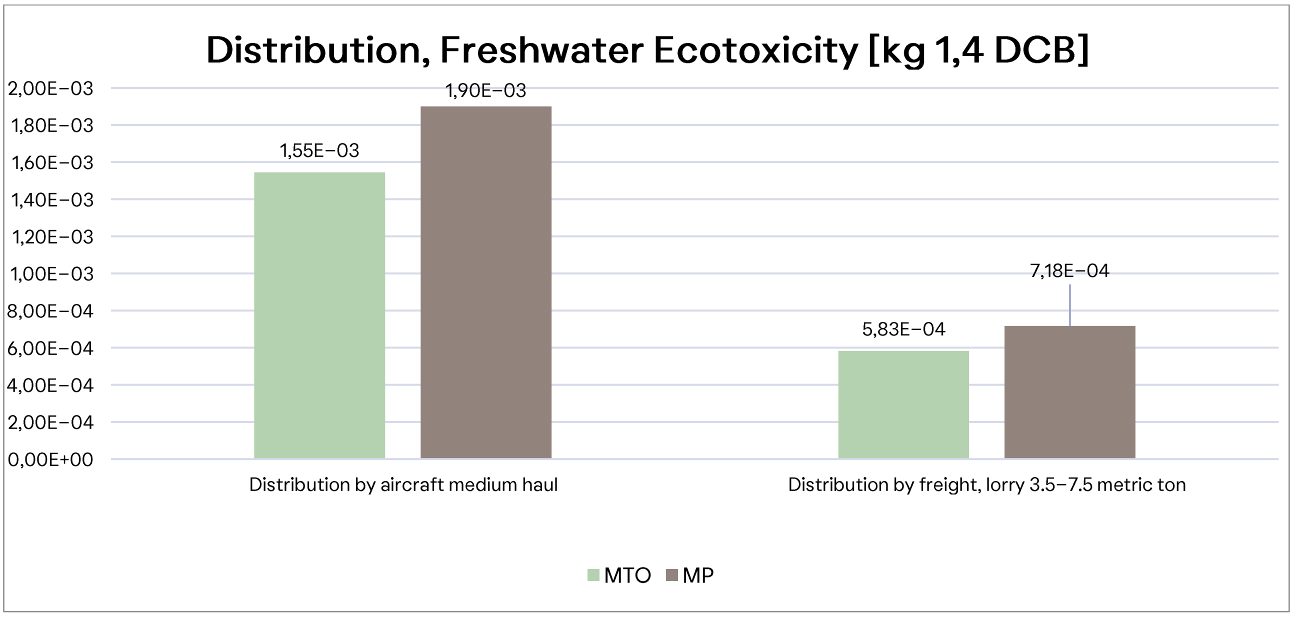

Figure 6.24: Freshwater Ecotoxicity, distribution

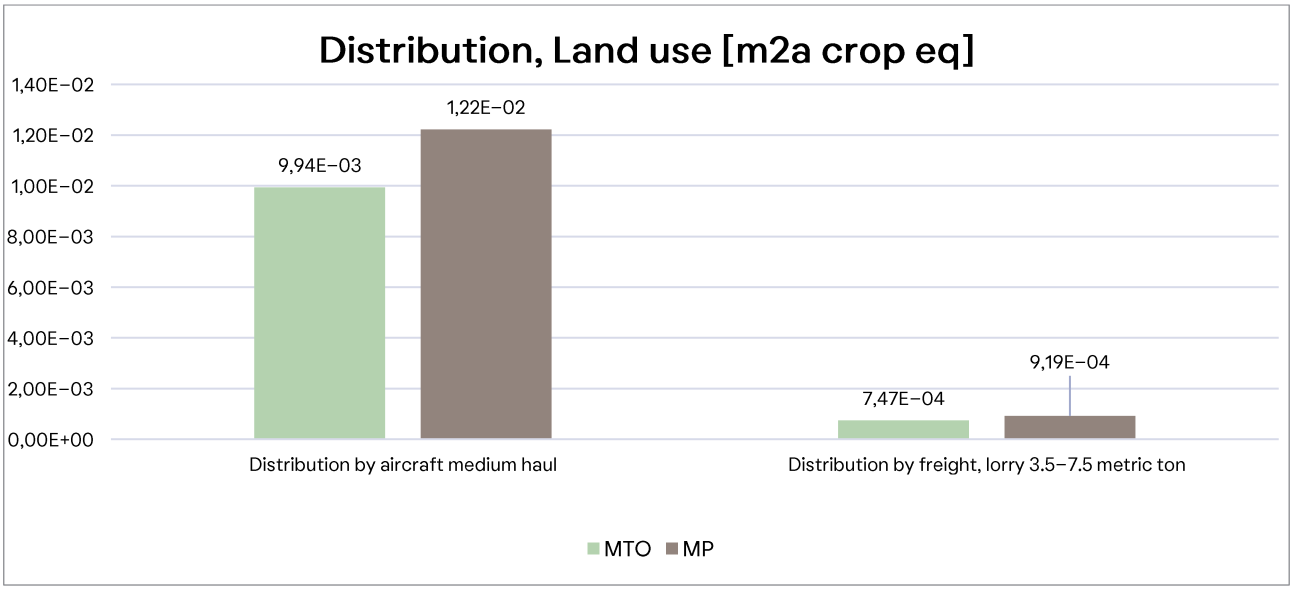

Figure 6.25: Land Use, distribution

In all four impact categories, the transport by aircraft is by far the most contributing factor in the distribution phase. This is both due to the amount of km transport for the aircraft but also due to emissions during flight and the construction of the aircraft.

6.1.1.7 Use phase contribution

For the use–phase, both laundry detergent, electricity and water are used. How these impact the use phase for the T–shirt is explored in this next section. Below, graphs for each of the four impact categories are shown.

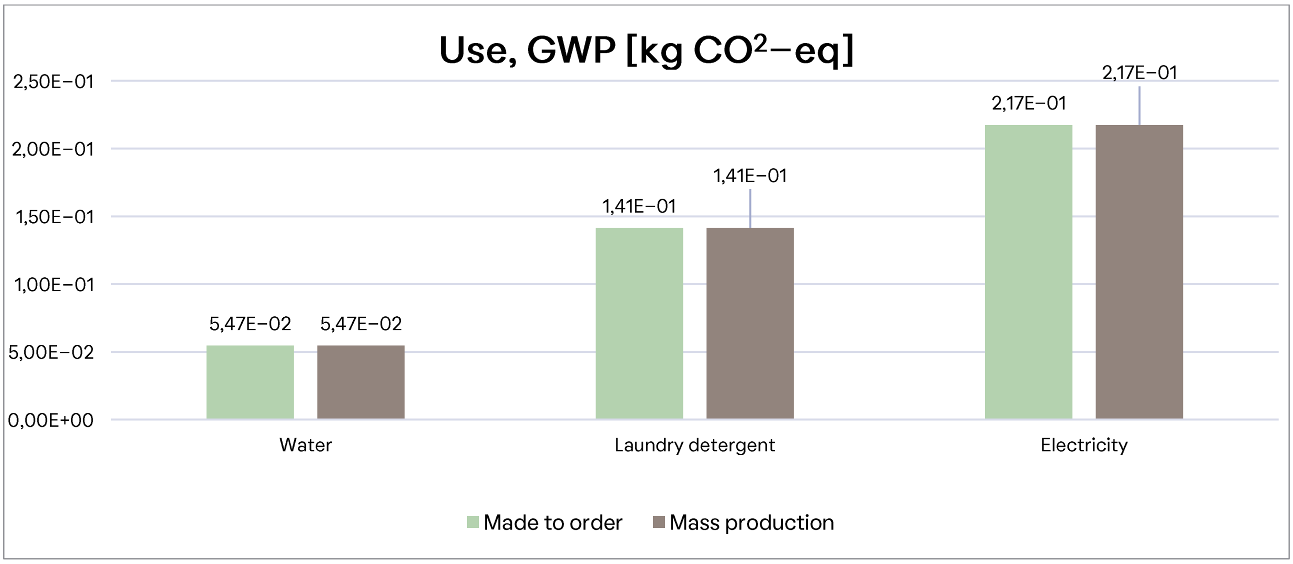

Figure 6.26: Global Warming Potential, use phase

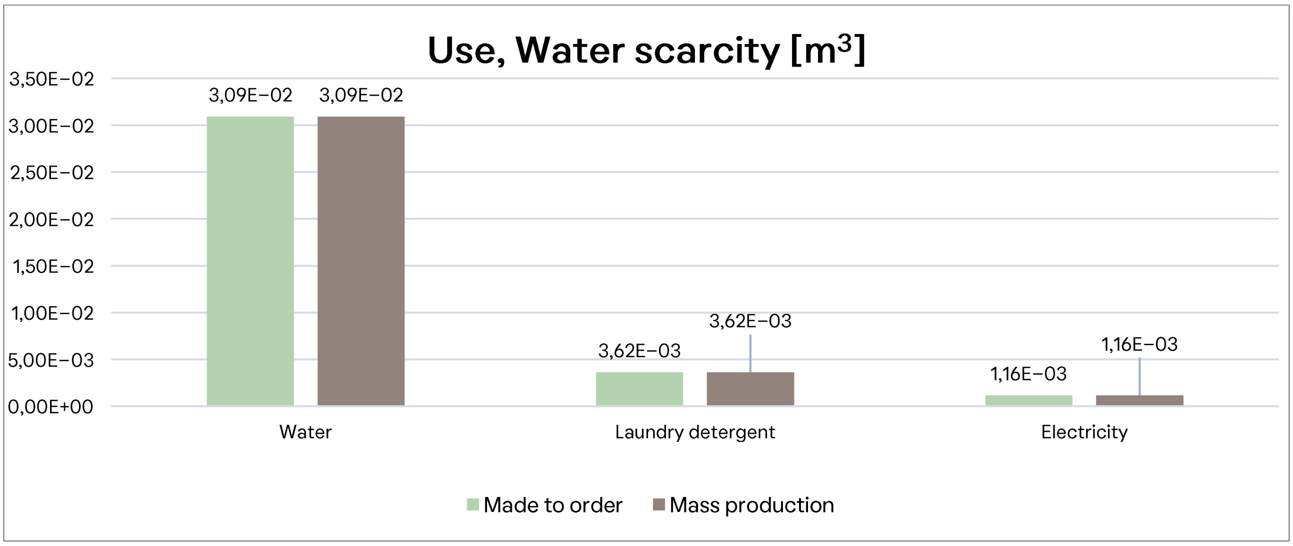

Figure 6.27: Water Scarcity, use phase

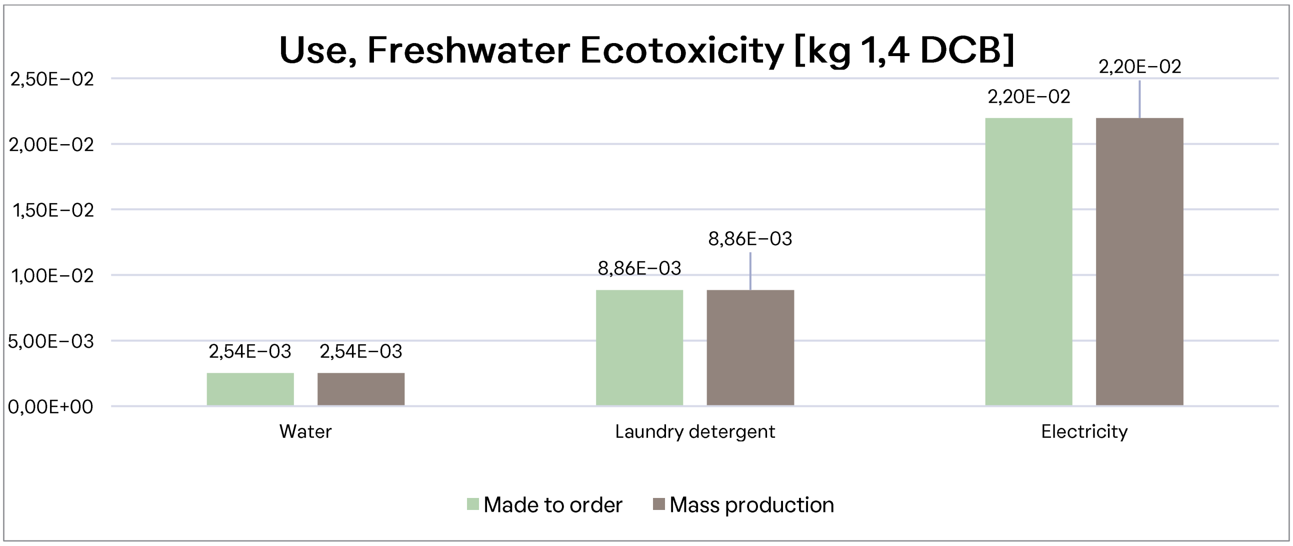

Figure 6.28: Freshwater Ecotoxicity, use phase

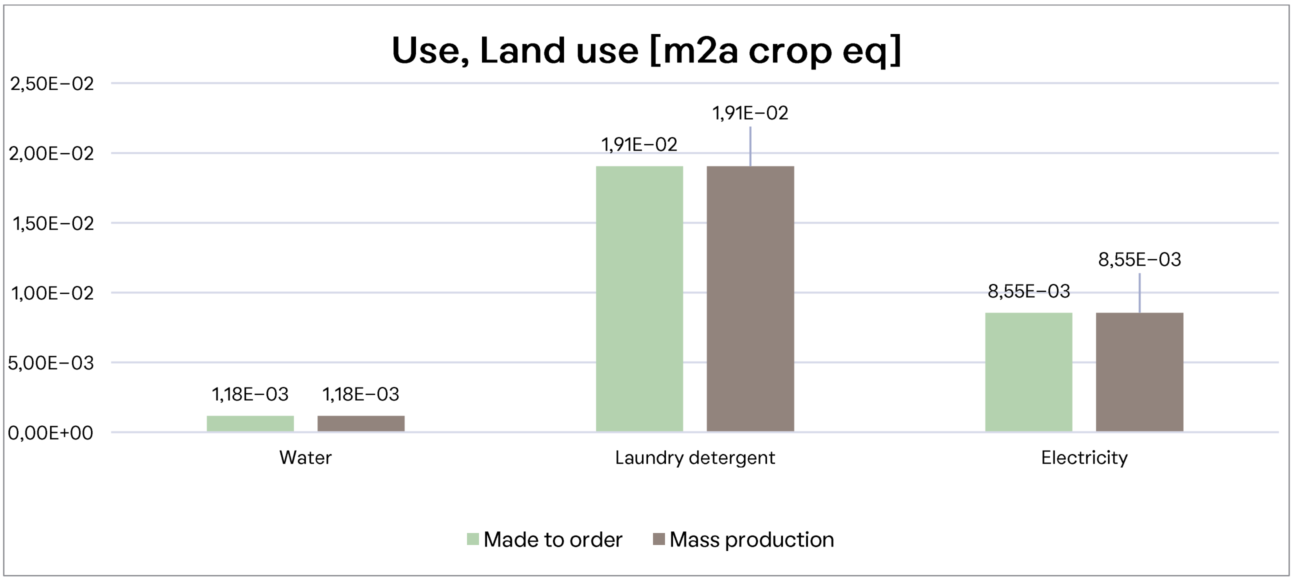

Figure 6.29: Land Use, use phase

In the Global Warming Potential category, the electricity for the use phase is the largest contributor due to the amount of kwh used for the T-shirt life span. The laundry detergent is the second largest contributor due to its composition and its component fluorescent production (FWA).

In the Water Scarcity category, it is the tap water used for the washing machine that has the largest contribution, meaning the water consumption for the T-shirt's life cycle.

In the Freshwater Ecotoxicity category, it is mainly the electricity use contributing to the impact, and not the laundry detergent, even though it consists of chemicals. This is due to the production and distribution of electricity influencing the freshwater. The amount of electricity thereby overpowers the little amount of chemicals in the laundry detergent.

In the Land Use category, the most contributing process is the laundry detergent. This stems from the input of use of enzymes from which it is the production of enzymes that causes the impact on land use. The land use for enzymes can be traced back to the harvesting of potato starch used for said enzymes.

6.1.1.8 End-of-life of used T-shirt process contribution

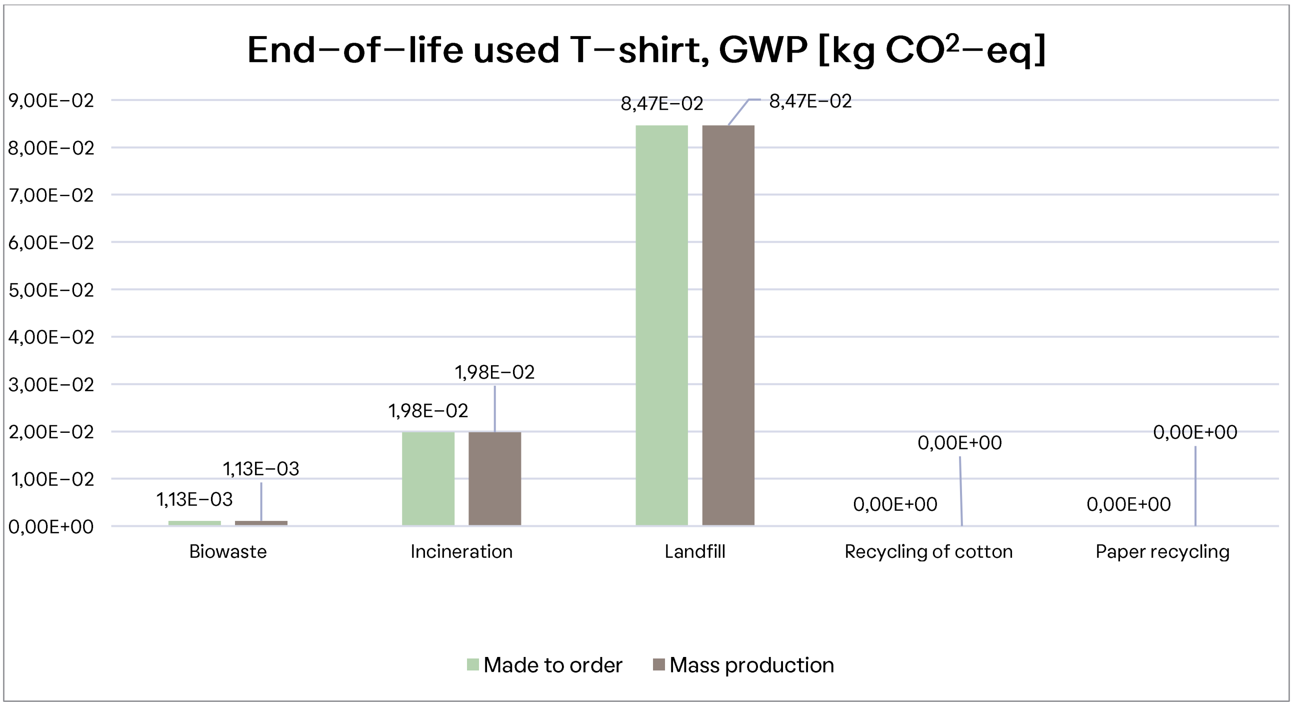

Figure 6.30: Global Warming Potential, end–of–life

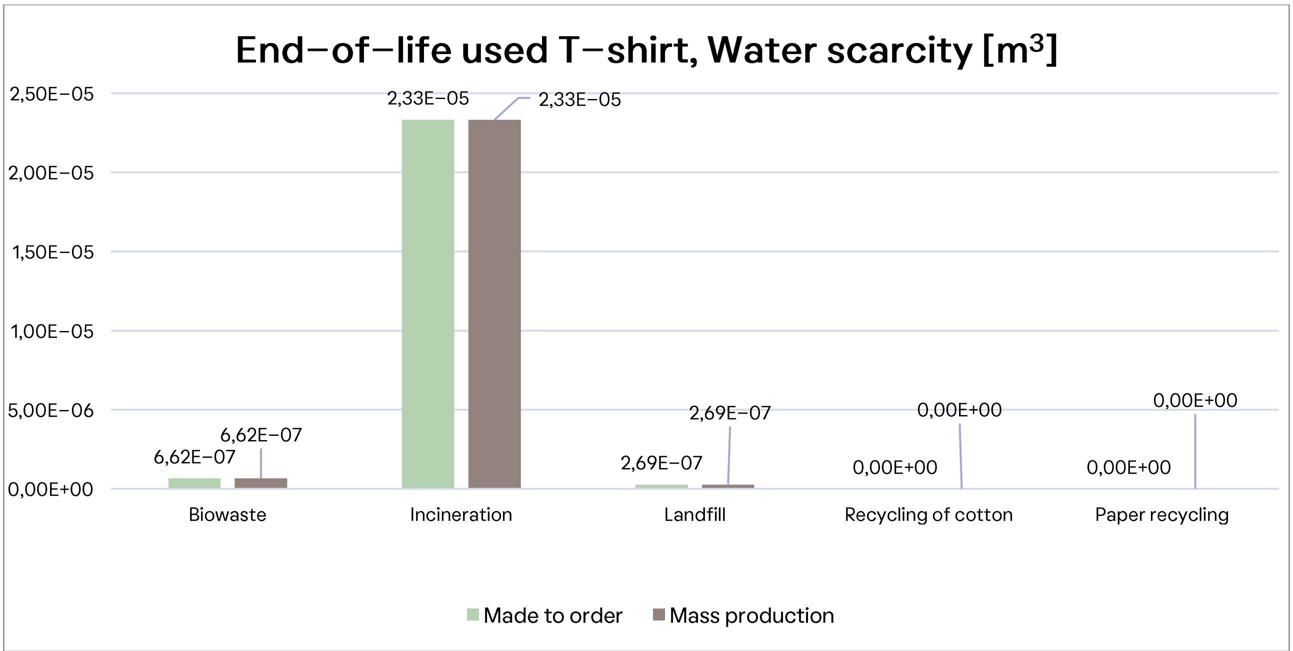

Figure 6.31: Water Scarcity, end–of–life

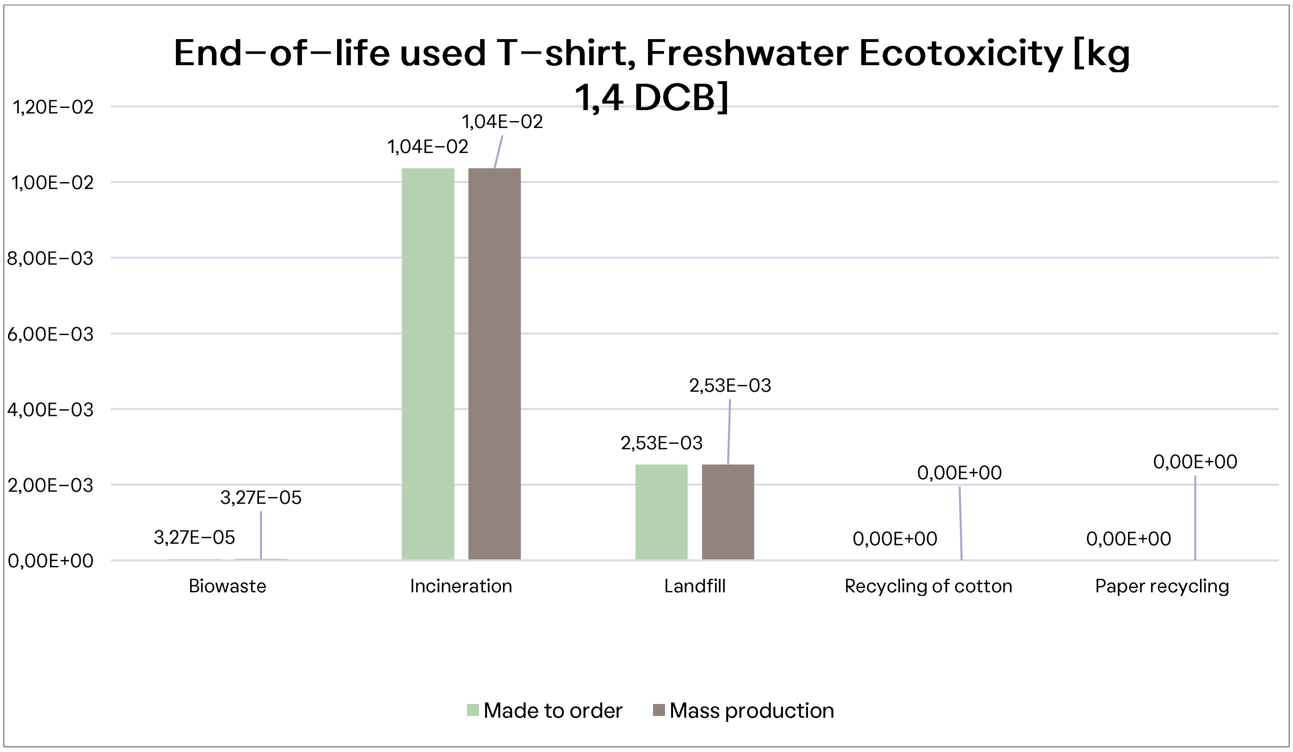

Figure 6.32: Freshwater Ecotoxicity, end-of-life

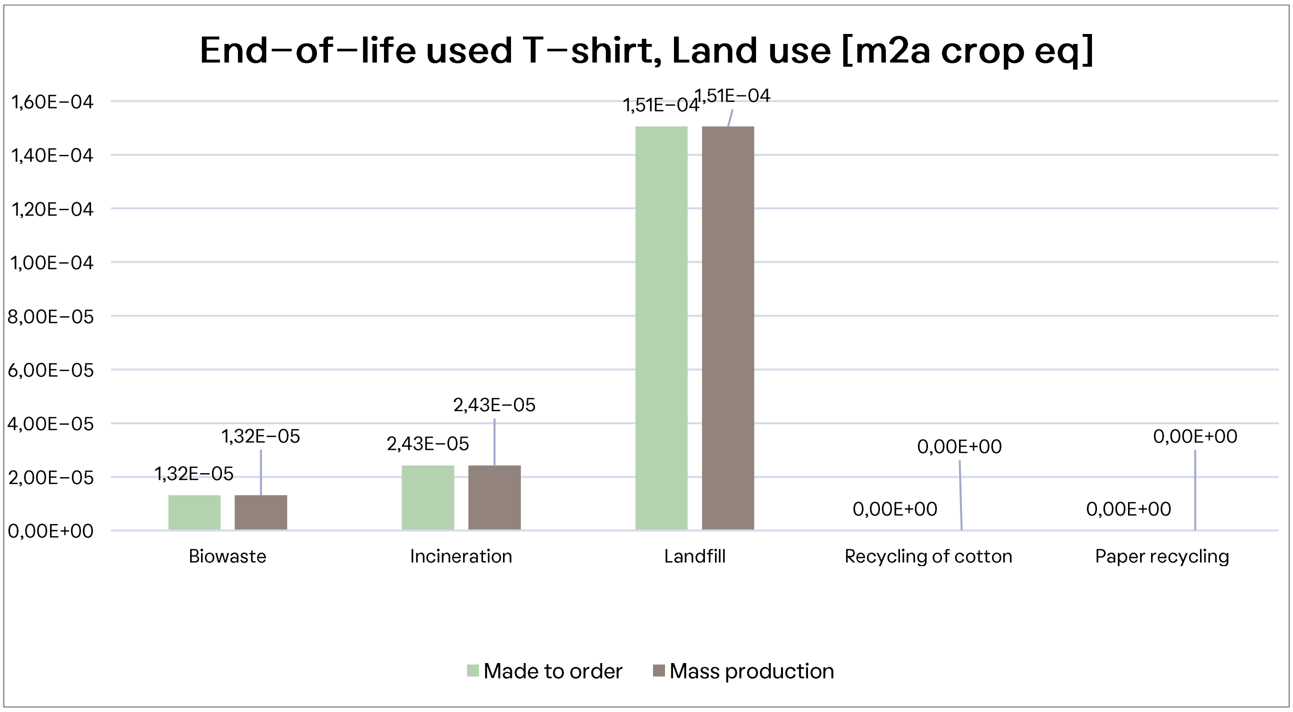

Figure 6.33: Land Use, end-of-life

In the Global Warming Potential category, the most contributing process is the waste treatment of sending the T-shirt to landfill due to the biogenic carbon emissions related toin this process. The landfill scenario is also the scenario where most of the T-shirt (58 %) is treated compared to the other scenarios based on the literature findings.

In the Water Scarcity category, incineration has the largest impact. This is caused by the consumption of water in the process for incineration. Although incineration has the most significant impact in water scarcity on the end–of–life phase, it is important to mention that the impacts in this phase are still low in relation to the overall impact.

In the Freshwater Ecotoxicity category, the incineration scenario has the largest contribution due to its emission to water in the process.

In the Land Use category, Landfill is the largest contributor due to the amount of waste going to landfill (58% of the T–shirt weight).

6.1.1.9 End-of-life of returned T-shirt process contribution

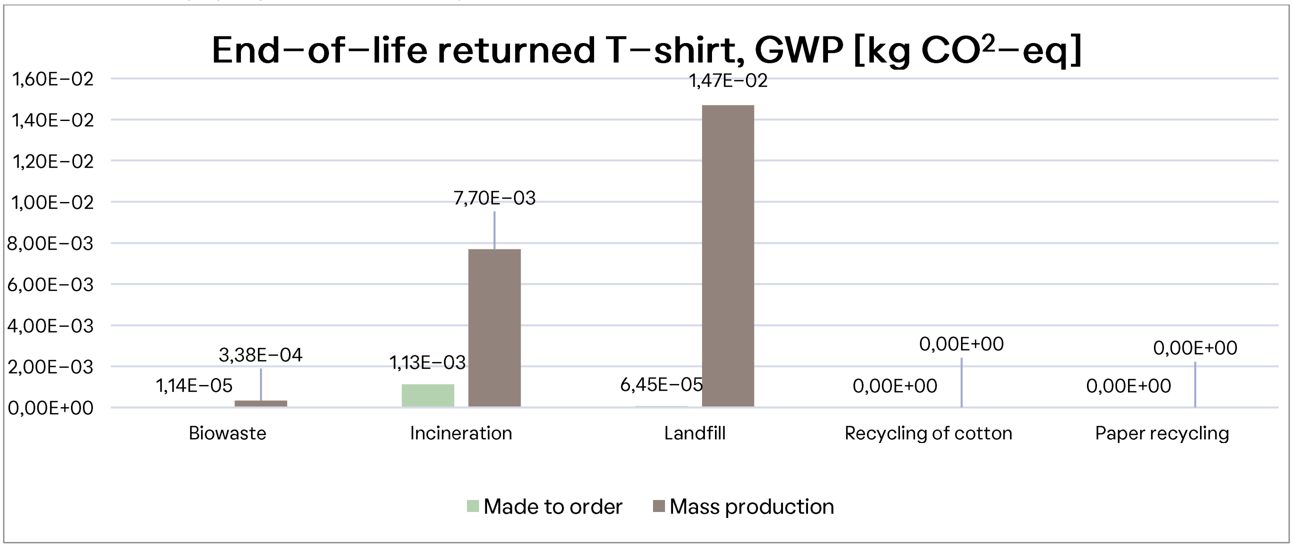

Figure 6.34: Global warming potential, end–of–life returned T–shirt

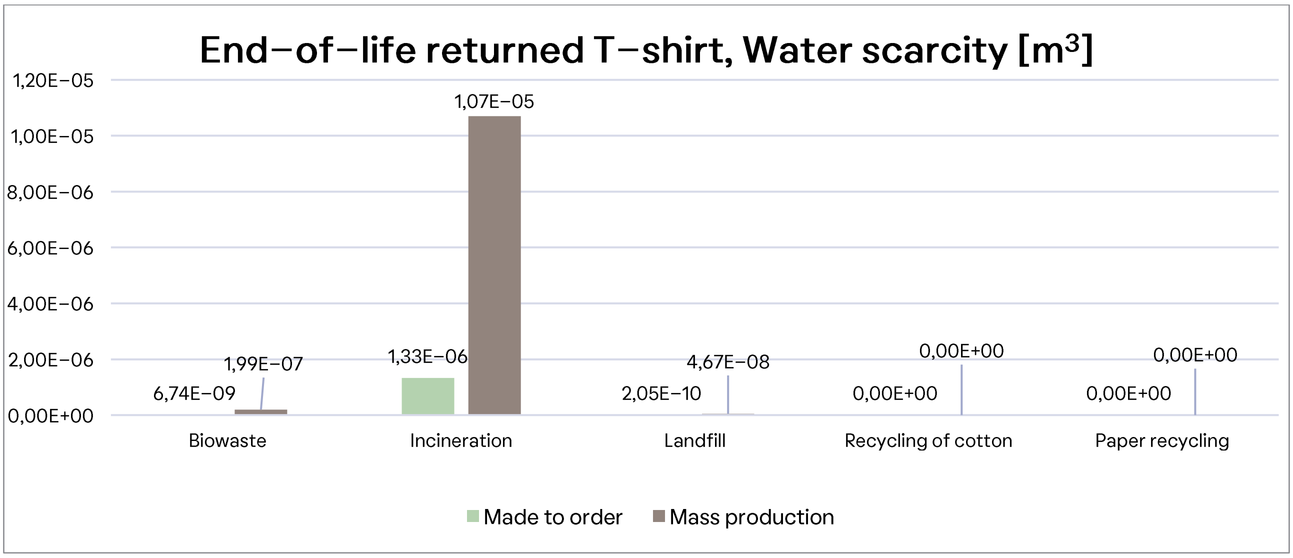

Figure 6.35: Water scarcity, end–of–life returned T–shirt

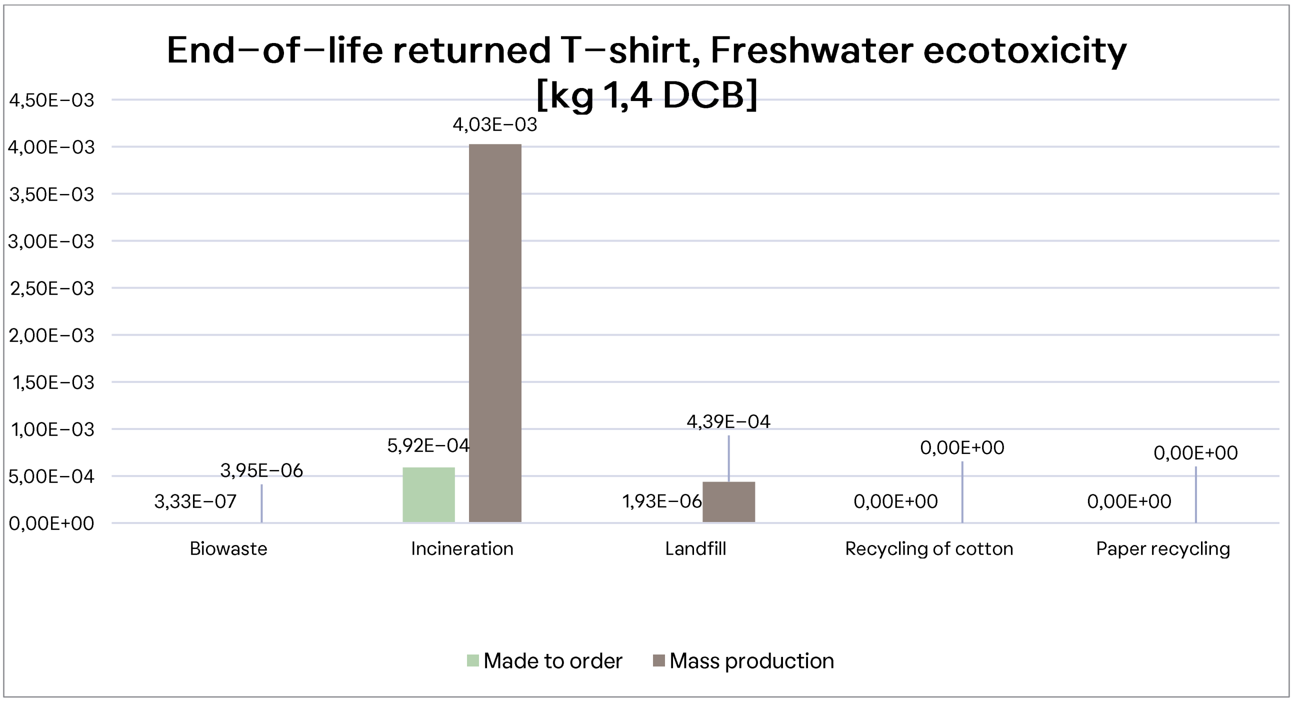

Figure 6.36: Freshwater ecotoxicity, end-of-life returned T-shirt

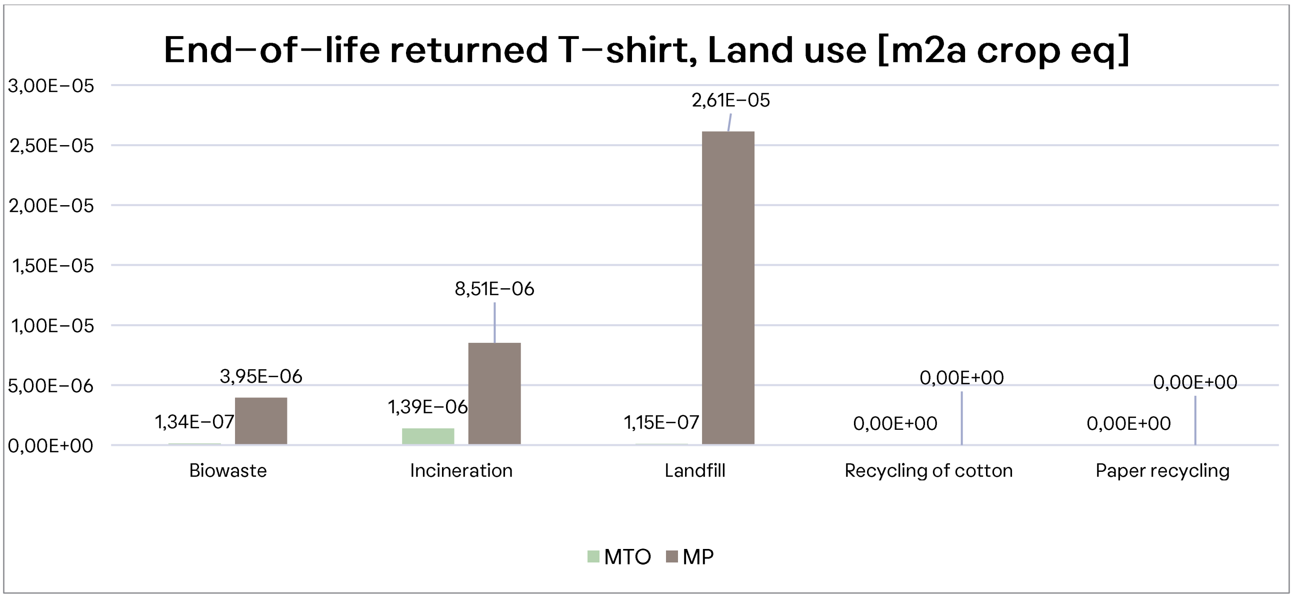

Figure 6.37: Land use, end-of-life returned T-shirt

In the Global Warming Potential category, the most substantial impact stems from waste sent to landfill due to the release of biogenic carbon emissions in the landfill process. Furthermore, a total of 58% of the T-shirt's weight ends up in the landfill.

In the Water Scarcity category, incineration has the largest impact, stemming from the consumption of water inherent in the incineration process. Water in incinerators is often used for temperature control, cleaning and maintenance as well as emission control and steam generation. While incineration has the most significant impact in water scarcity on the end-of-life phase, it is important to note that the impacts in this phase are still low in relation to the overall impact.

In the Freshwater Ecotoxicity category, the incineration scenario is a primary contributor, due to its emission to water in the process.

In the Land Use category, landfill is the largest contributor due to landfilling taking up a substantial amount of space, as well as it having the largest input of waste (58% of the T–shirt).

6.1.1.1 End-of-life of deadstock (mass production only)

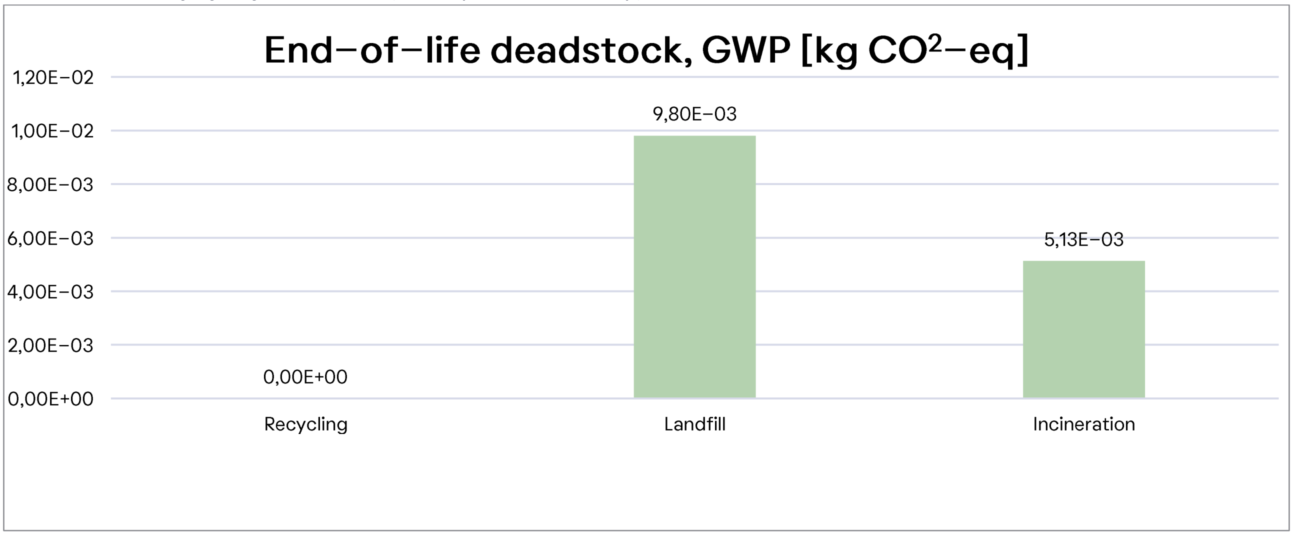

Figure 6.38: Global warming potential, end–of–life deadstock

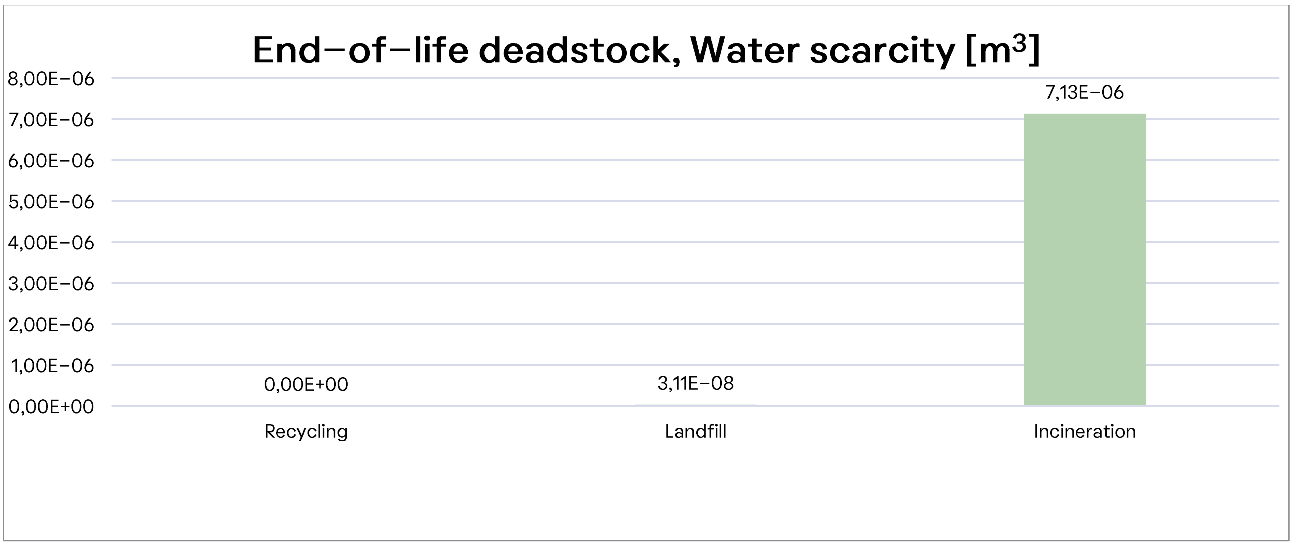

Figure 6.39: Water scarcity, end–of–life deadstock

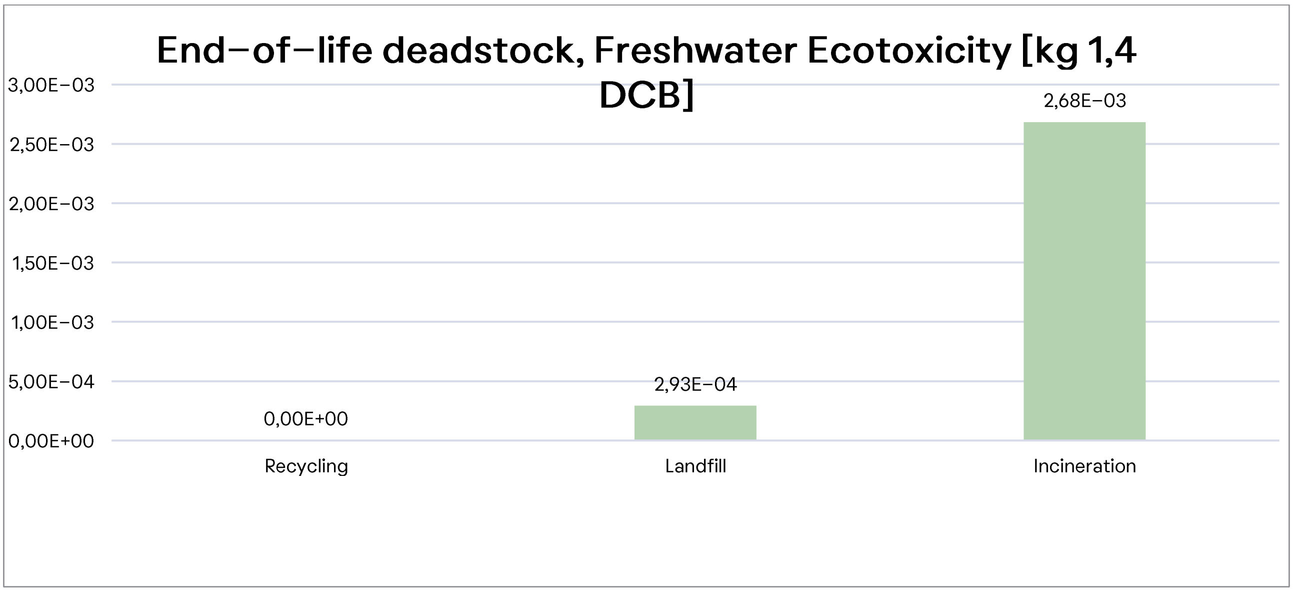

Figure 6.40: Freshwater ecotoxicity, end–of–life deadstock

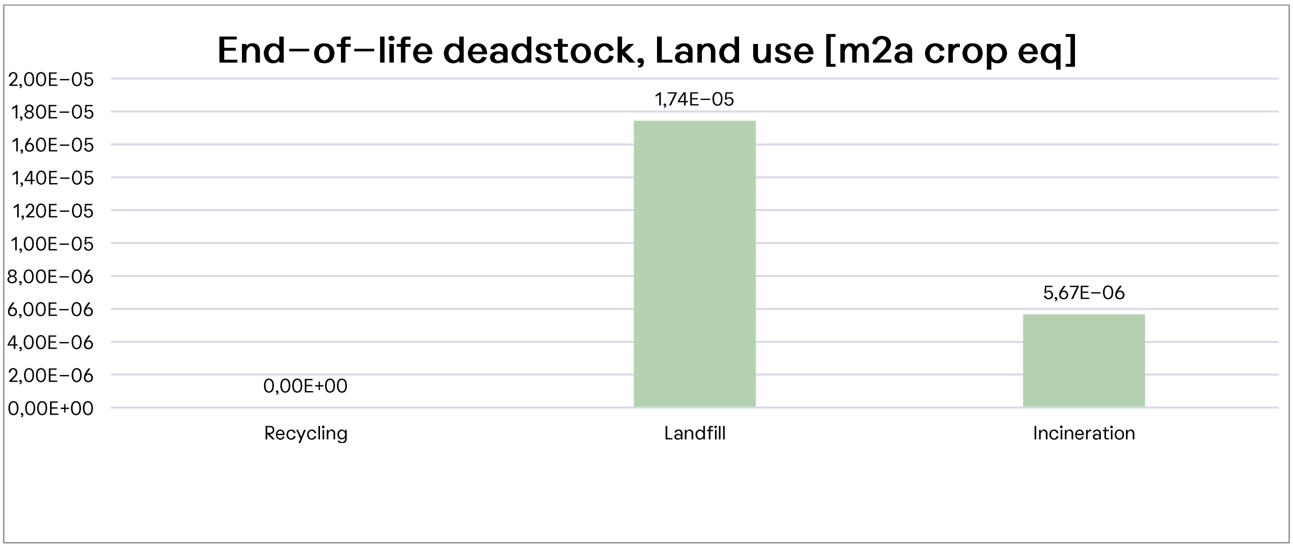

Figure 6.41: Land use, end–of–life deadstock

In the Global Warming Potential category, landfill has the largest impact due to the release of biogenic carbon emissions in the landfill process.

In the Water Scarcity category, the largest contribution stems from incineration, due to the consumption of water inherent in the incineration process.

In the Freshwater Ecotoxicity category**,** the largest contribution comes from the incineration scenario due to its emission to water in the process.

In the Land Use, landfill is the largest contributor due to landfilling taking up a substantial amount of space, as well as it is having the largest input of waste (58% of the T–shirt).

6.1.2 Appropriateness of the defined system

The defined system and system boundaries for this LCA represents Son of a Tailor's actual production and their supply chain and processes. The way the T–shirt is modeled is a good representation of how the T–shirt is produced and distributed in real life. The functional unit considers that Supima cotton has a better technical performance than regular cotton, which is reflected in the estimated amount of times the T–shirt will be washed in its lifetime. Regarding the MP system, this represents a hypothetical scenario of how a production system would look like if Son of a Tailor implemented a mass production business model. The application of production data is uniform across the MP system and MTO system, encompassing data from both tier 1 and tier 2, with the exception of an inclusion of an additional 20% deadstock and 30% return rate in the MP system. It cannot be dismissed that if Son of a Tailor were to use a MP business model, it might change some of their suppliers, but since the material and production methods will likely be the same, it would only affect the transport of raw materials. Since transport of materials to production has a very low impact on the overall life cycle it would not change the results significantly, meaning the way the system is defined is considered reasonable. The defined system for both MTO and MP are specific for Son of a Tailor's unique production processes. As a result, the outcomes of this LCA study exclusively showcase the advantages that Son of a Tailor gains from adopting an MTO business approach instead of an MP business approach. The reason behind this is that the system is customized to Son of a Tailor's operations, and therefore it does not represent any other company or generic textile production, thus limiting the comparison between the MTO and MP business models to Son of a Tailor only. The goal and scope of the study is first and foremost to assess the impact on the MTO business model and the MP business model to understand the saving by producing a T–shirt on demand versus forecasting. Since it is known that the mass production business model has deadstock waste and return rates due to the nature of standardized clothing sizes, these factors are accounted for in defining the MP system. In can be discussed what the percentages for deadstock waste and return rates would be in a MP business model, and in the real world these percentages will differ from business to business. This is why averages of both deadstock and return rates have been utilized in this study, albeit still with specific data matching Son of a Tailor's production to be as representative as possible. This also means that the environmental difference between the MTO and the MP business model in this study is only applicable for the used percentages of deadstock and return rates. If other values were assessed, the results would change accordingly. The second goal and objective of the study has been to calculate the baseline for Son of a Tailor's Supima cotton T–shirt in a cradle–to–grave perspective. Here the defined system and functions are considered, for example by including user behavior of washing a T–shirt, and how the waste treatment will affect the impact of the T–shirt.

6.1.3 Effect of cut–off criteria

The 1% cut–off criteria from the inventory and impact assessment have shown to have very little effect on the overall results. This is because a lot of the desired data were able to be collected and used in this LCA study. The excluded processes due to the 1 % cut–off criteria are mostly packaging for laundry detergent and the printing of neck and care labels. These exclusions would be added to both the MTO and MP system, and so it can be expected, that the conclusion that Son of a Tailor's MTO business model has a general lower impact than the MP business model will not be affected. The impacts on the baseline of the MTO system will be affected, but this change is expected to be minor due to the relatively low inputs something like printing on labels and packaging for laundry detergent would give. The cut off system model used does have an influence, since benefits of recycling cotton are allocated to the next product system. These benefits would favor both business models, but mostly the MP system. This is due to more waste being generated in this business model because of the 20% deadstock and 30% returns per T–shirt, and thereby more waste would be sent to recycling compared to the MTO system. If inclusion of such benefits were accounted for, the increase of impact from the MTO system to the MP system would be smaller. But the MTO system would still have less impact compared to the MP system if benefits of recycling were accounted for.

6.1.4 The comparison between MTO and MP

From these different viewpoints in impact categories and from the different life cycle phases a Supima cotton T–shirt goes through, it is obvious that the MP business model generally has a higher impact. This is the case across all impact categories and phases. The main reason behind this is that more material is needed to produce one T–shirt in an MP model due to the deadstock waste, as well as the higher return rates caused by the lack of custom fits.

The MP business model increases the Global Warming Potential with 29,66% compared to the MTO business model in a cradle–to–grave perspective. This means that based on this analysis, the MTO business model is a less polluting business model than MP.

In the Water Scarcity category, the MP business model increases the footprint with 30,01% compared to the MTO business model in a cradle–to–grave perspective.

In the Freshwater Ecotoxicity category, the MP business model increases the footprint with 33,97% compared to the MTO business model, mainly due to the fertilizer used in the growing and harvesting of cotton seed in the raw materials phase. Since the MP model needs more material due to deadstock and return rates, the MTO model performs better than the MP business model in the cradle–to–grave perspective.

Lastly, in the Land Use impact category, the MP business model increases the footprint with 40,36% compared to the MTO business model. It is also evident that it is mostly the land use for the cotton seeds that contributes, and because the MP model has more material input, it eventually has a higher impact in this category as well.

6.2 SENSITIVITY CHECK

In this section, the sensitivity of the modelling will be checked through a contribution analysis, as well as an analysis on the end–of–life modelling, and an analysis on the methods used for water footprint and ecotoxicity.

6.2.1 Contribution analysis

For the contribution analysis the most significant life cycle phases have been investigated based on the most significant process from said phases.

6.2.1.1 Raw materials – cotton ginning

The largest contributor to the overall impact is the raw materials phase. In this phase cotton harvesting, ginning, and pressing, is a big contributor, and so it is necessary to investigate the process further.

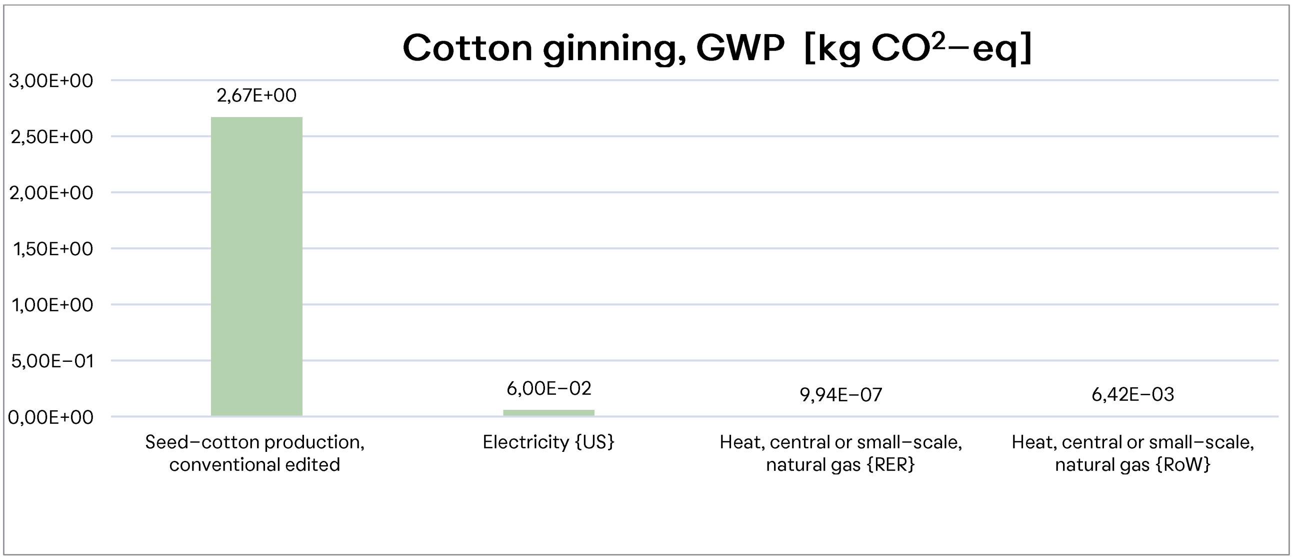

Figure 6.42: Global warming potential, cotton ginning

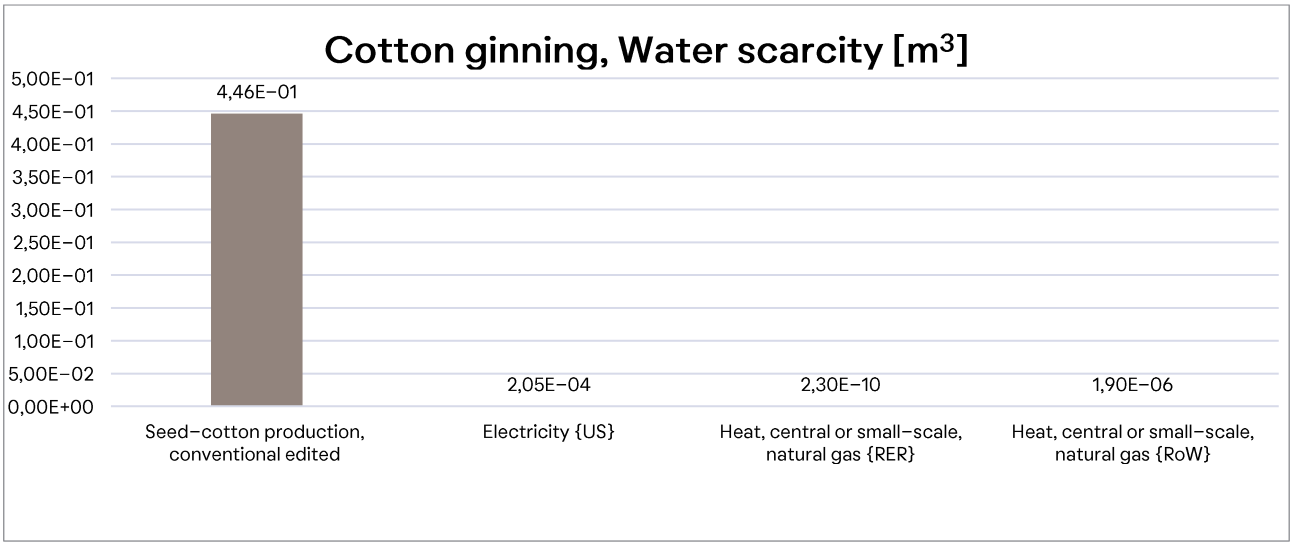

Figure 6.43: Water scarcity, cotton ginning

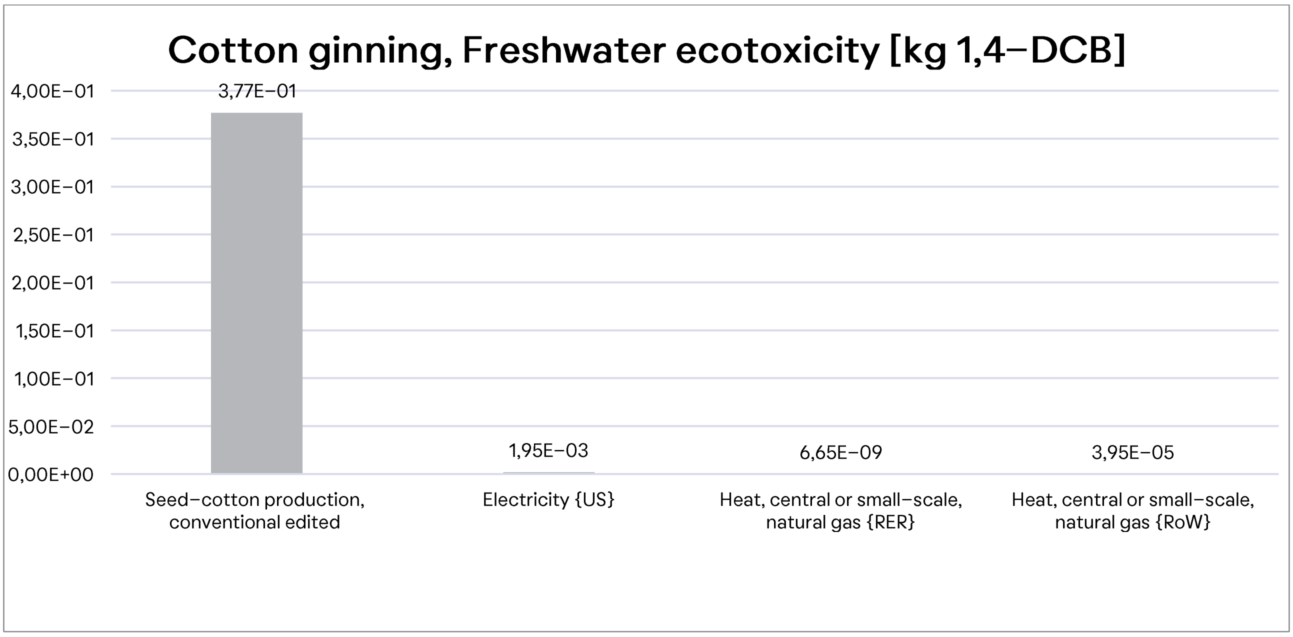

Figure 6.44: Freshwater ecotoxicity, cotton ginning

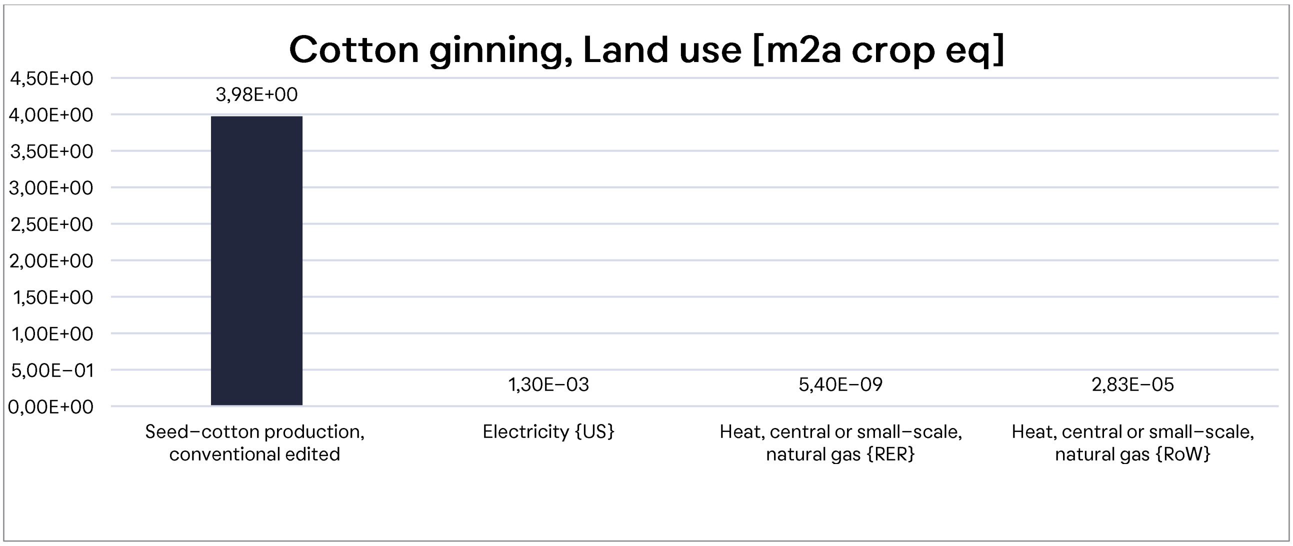

Figure 6.45: Land use, cotton ginning

In all impact categories, the seed cotton production has the largest impact, which will be the biggest trigger for a change in results. The process for cotton seed production will be investigated further in the following section.

6.2.1.2 Raw materials – cotton seed production

The seed cotton employed in the modelling of this LCA has undergone adjustments to align with Son of a Tailor's production line, meaning the production of cotton seed in the US only. These modifications entail adjusting the electricity and water inputs from a global mix to US processes. Therefore, the adjusted process will be compared to the original cotton seed production process. Additionally, the process for organic cotton seed will be investigated. The following graph shows a comparison between these three processes based on 1kg cotton seeds.

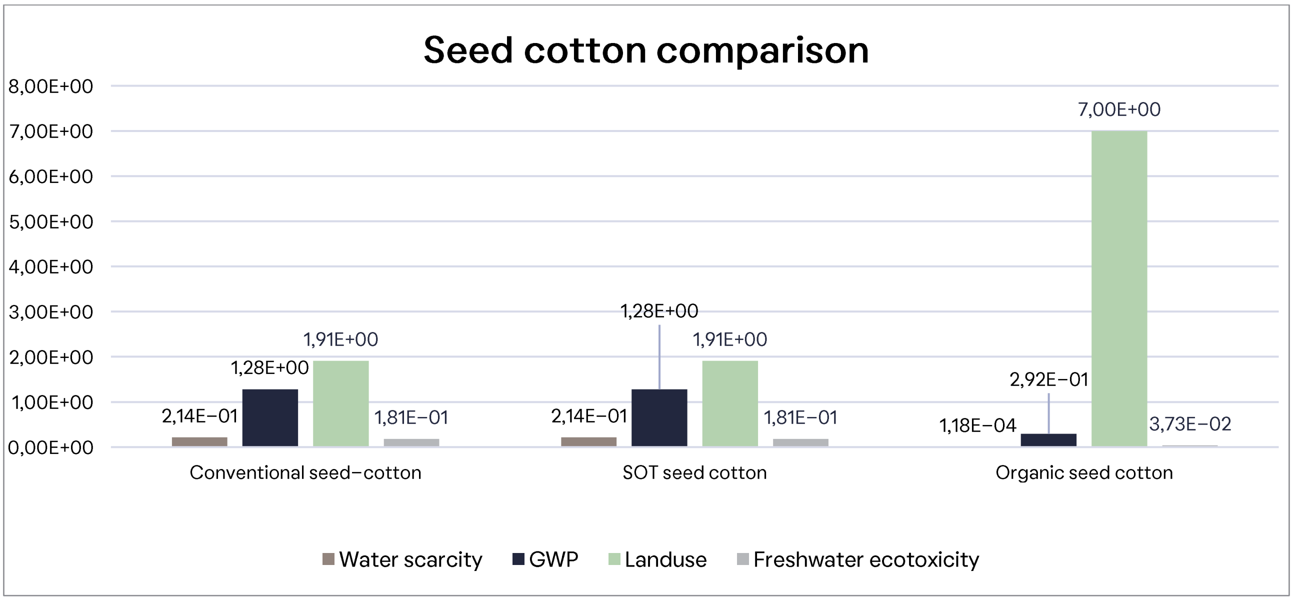

Figure 6.46: Seed cotton comparison

As seen in the graph above, conventional seed cotton and the edited seed cotton process (SON seed cotton) for Son of a Tailor are almost identical, with only a 0,03% increase in global warming potential in the edited version of the cotton seed. In contrast to this, organic seed cotton has a much larger contribution in Land Use, but a smaller contribution in Global Warming Potential, Water Scarcity and Freshwater Ecotoxicity than both the conventional cotton seed process and the edited cotton seed process. This is caused by organic farming practices, which creates a lower yield, since the use of GMOs and synthetic pesticides are not allowed for this type of farming. Instead the practices rely on other methods like crop rotation, companion planting and organic fertilizers. Crop rotation, in particular, requires larger land areas to effectively rotate crops and manage soil fertility. However, as seen in the lower Global Warming Potential and Freshwater Ecotoxicity impact categories, there are also benefits to not having an input of synthetic fertilizers, pesticides, and herbicides. Another cause for the lower Global Warming Potential impact of organic seed cotton is that organic farming helps enhance the content of organic matter in soil, which leads to a better carbon sequestration. Since Supima cotton is not a certified organic cotton material, the modified conventional seed cotton is deemed reasonable for this LCA study.

6.2.1.3 Raw materials – yarn ring spinning

While cotton production, including ginning and farming of cotton seeds, is the highest contributor to the raw material phase, yarn ring spinning also has a significant impact. Therefore, Global Warming Potential impact of the process of yarn ring spinning has been investigated.

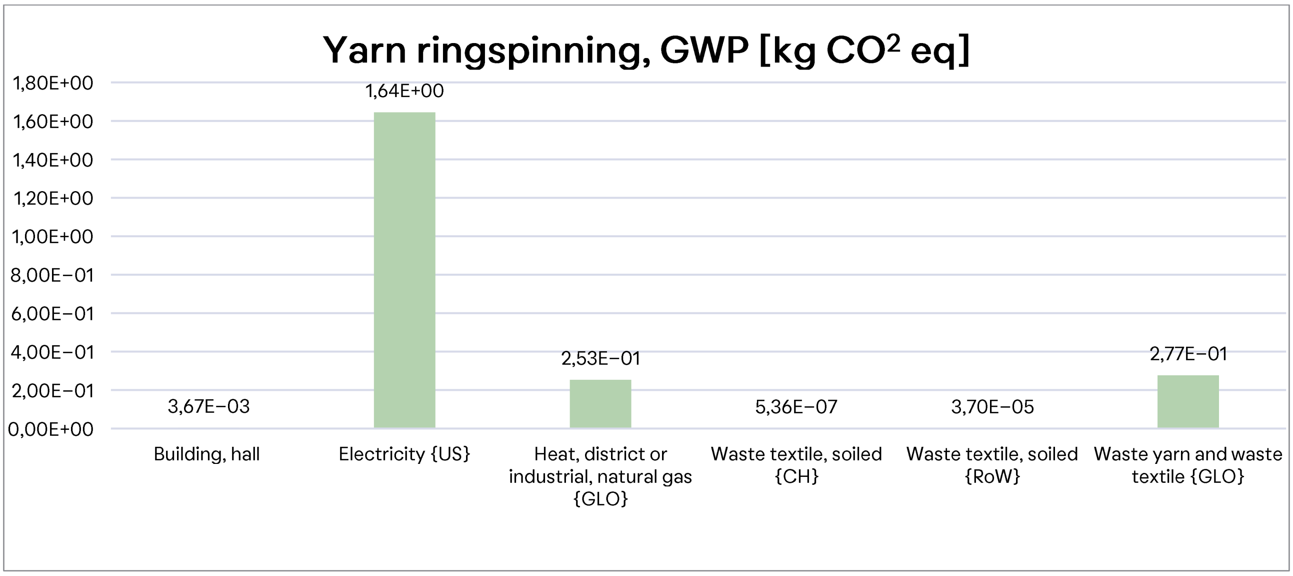

Figure 6.47: Global warming potential, yarn ring spinning

The impact of yarn ring spinning comes mainly from the use of electricity. The electricity is modelled on a US mix process, but the amount of electricity input has not been changed from the original process, since data on this was not available from the supplier. It can be concluded that the use of electricity has a large impact on yarn ring spinning and in turn the overall results. However, it is deemed to be a reasonable estimation based on the available data and geography of the cotton production.

6.2.1.4 Fabric knitting – dyeing and finishing

In fabric knitting, the most contributing process is dyeing and finishing. This process is built on the batch dyeing process, and so it is relevant to compare these. Additionally, continuous dyeing which is an alternative to batch dyeing, will be used for comparison. The values on the graph corresponds to 1 kg of textile.

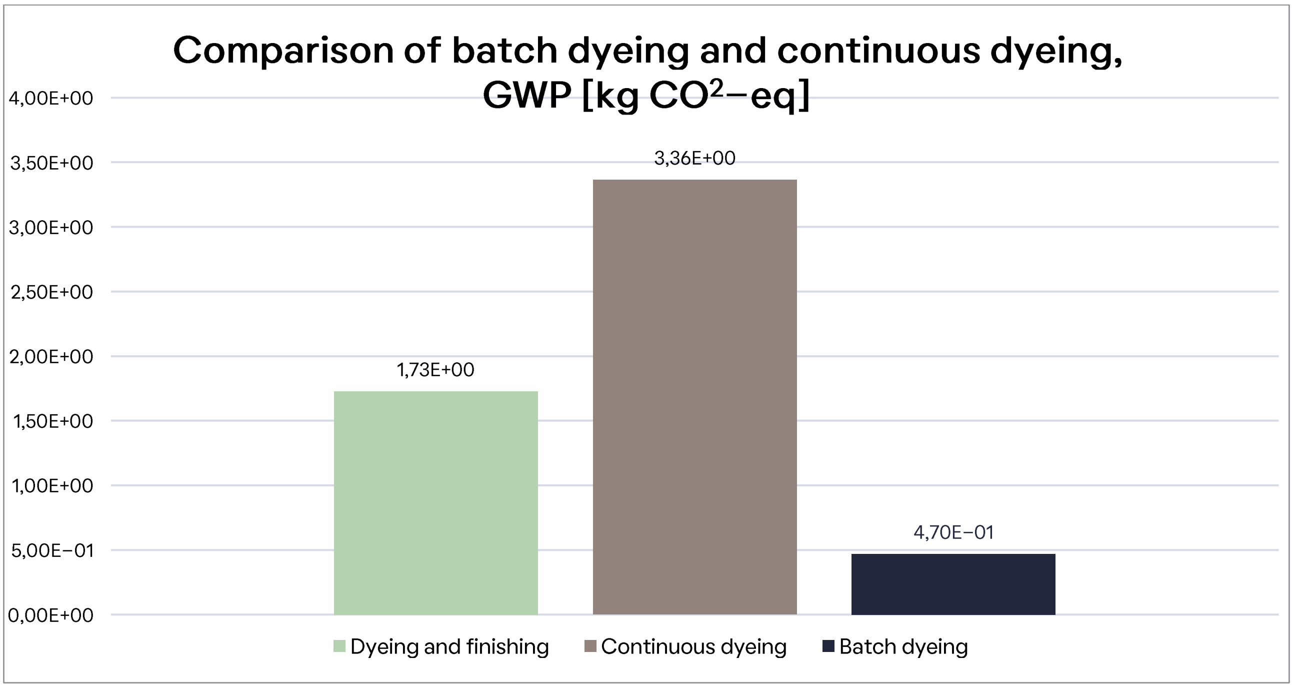

Figure 6.48: Comparinson of batch dyeing, continuos dyeing, and dyeing and finishing

From the graph it is evident that the dyeing and finishing process, which is an adjusted version of batch dyeing, has a higher impact than the original batch dyeing process. The batch dyeing process has a lower impact than the dyeing and finishing process of 73% per kg textile. This difference is caused by the electricity input and natural gas, where the specific numbers from Son of a Tailor's production show a larger contribution.

Continuous dyeing is a different dyeing process than batch dyeing, and since we know that Son of a Tailor uses batch dyeing, it is not directly comparable to their reality. It is however interesting to look at regarding recommendations to Son of a Tailor found at the end of this report. The batch dyeing process has a 95% larger impact per kg textile compared to the original dyeing and finishing process. To conclude, the impact from dyeing and finishing will vary greatly on electricity input as well as the type of dyeing process used in the production.

6.2.1.5 Use – laundry detergent

Since the soap process in the use phase has been created based on generic data on the detergent Tide, and since it is built on a generic soap process from SimaPro, it is relevant to explore the difference between the original soap process and the Tide process. This is explored in both Global Warming Potential, Land Use, Water Scarcity, and Freshwater Ecotoxicity, since it is expected that the difference in input between the two processes will influence all of these impact categories. The values in the graph correspond to 1 kg of soap.

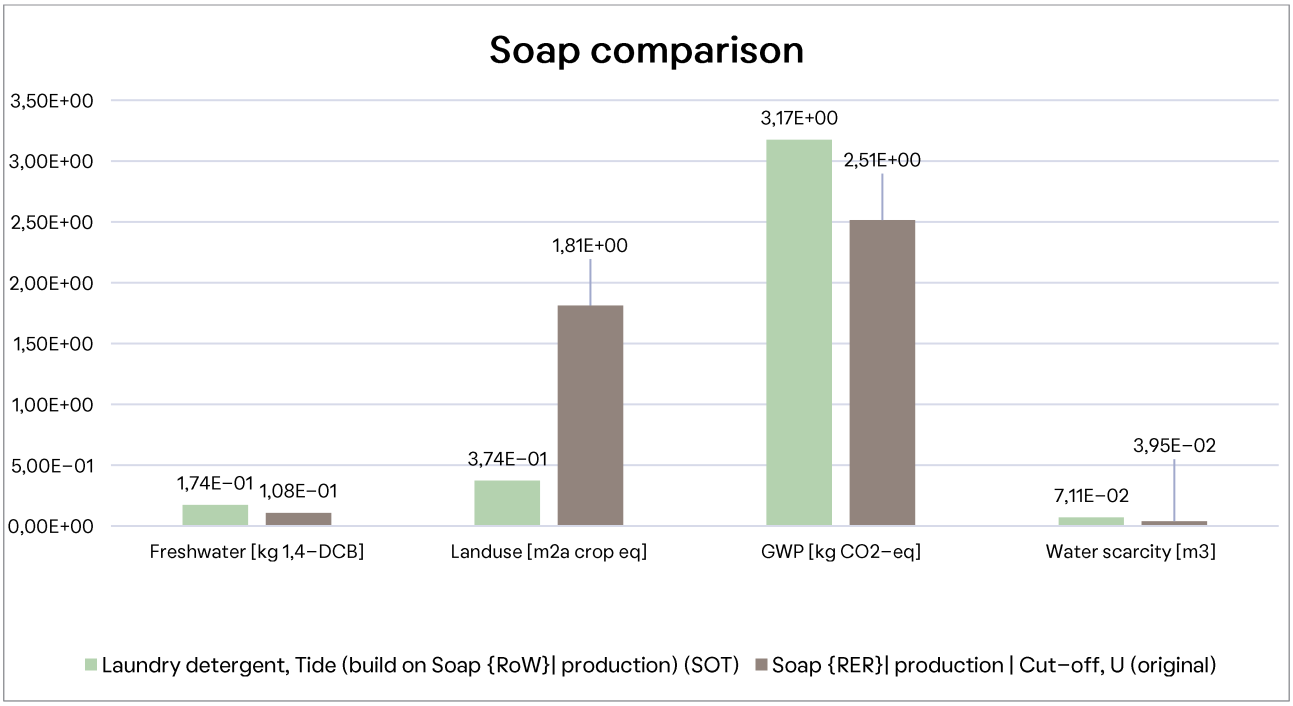

Figure 6.49: Comparison of soap processes

From the graph it is evident that the original soap process has higher Land Use impact, but a lower impact in both Global Warming Potential, Freshwater Ecotoxicity and Water Scarcity. Since the generic soap process is not a specific washing soap, the custom build soap based on information of the most used detergent is assessed to be the best and a reasonable choice.

6.2.1.6 Use – tumbledrying

The use phase is built on the assumption that the user does not tumble-dry their T-shirt due to instructions on the care label. To test what effect that has on the results, a use-phase including tumble-drying has been modelled for comparison. The tumble-drying is modelled by increasing the use of electricity.

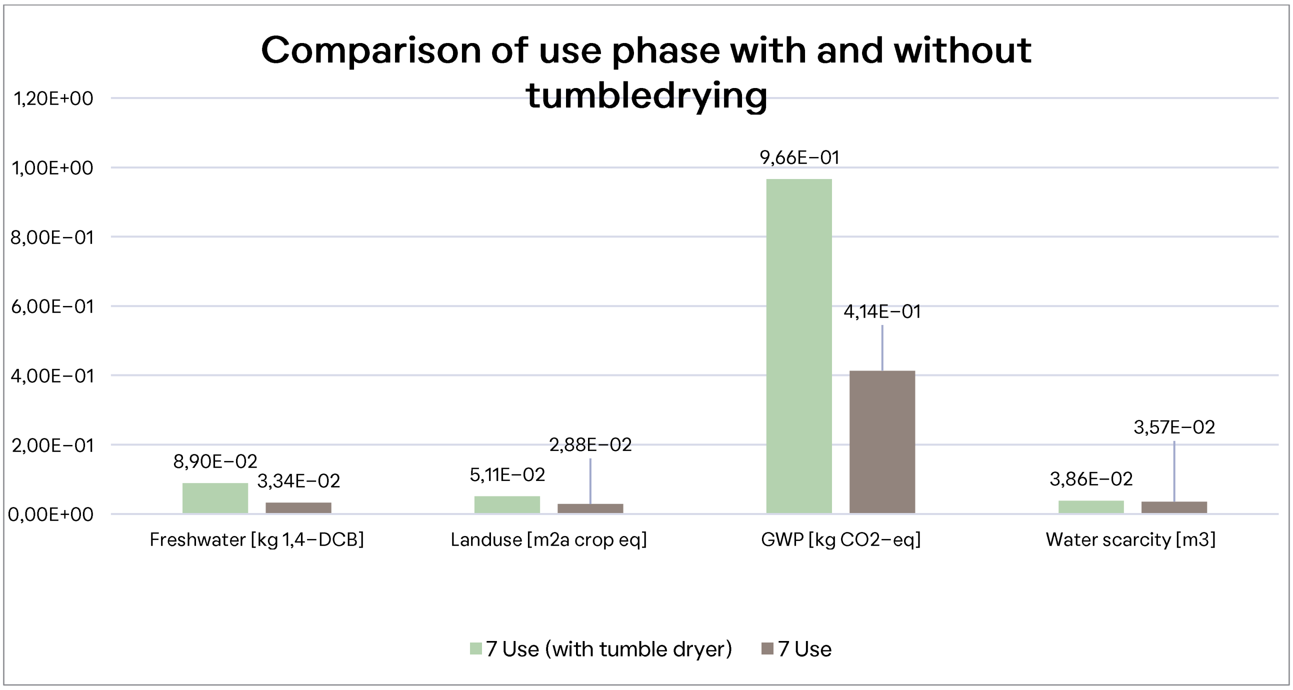

Figure 6.50: Comparison of use−phase with and without tumbledrying

It is seen from the graph above, that the use phase that includes tumble drying has an overall bigger impact in all impact categories, which comes from the added consumption of electricity from the tumble−drying process. This is especially true in the Global Warming Potential category, where if the user does use a tumble dryer, the GWP impact for the T−shirt in the MTO business model will increase with 16%. Ultimately, since it is stressed on the care label that the T−shirt should not be tumble dried, it still seems reasonable to exclude the process. However, it is recommended that Son of a Tailor continues to or improves their emphasis on creating awareness on the importance of not using a tumble dryer for their Supima cotton T−shirts.

6.2.1.7 Transportation and distribution – flight processes

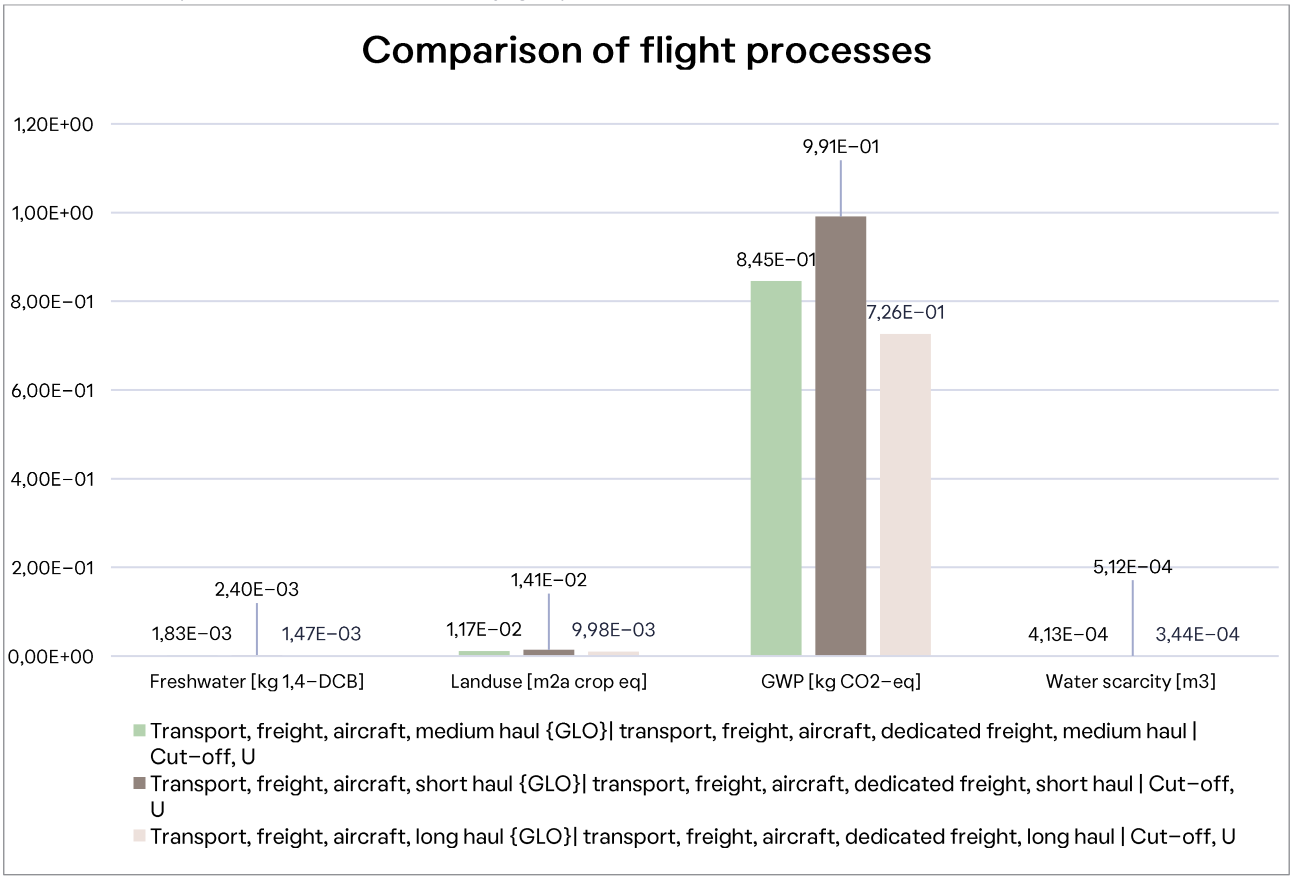

Figure 6.51: Comparison of long-, medium-, and short haul flight processes

From the graph above, it can be concluded, that the flight with the largest impact in all impact categories is the short haul flight. Transport by flight is a big contributor in transport to distribution as well as distribution. In transport to distribution, the choice of the medium haul flight process is evaluated to be reasonable since the distance travelled is only from Portugal to Copenhagen. In the distribution phase it can be difficult to evaluate which process would be the best, since the distances travelled to each customer will vary. Due to this variance, the choice of the medium haul flight is evaluated to be reasonable.

6.2.1.8 Transportation and distribution – lorry processes

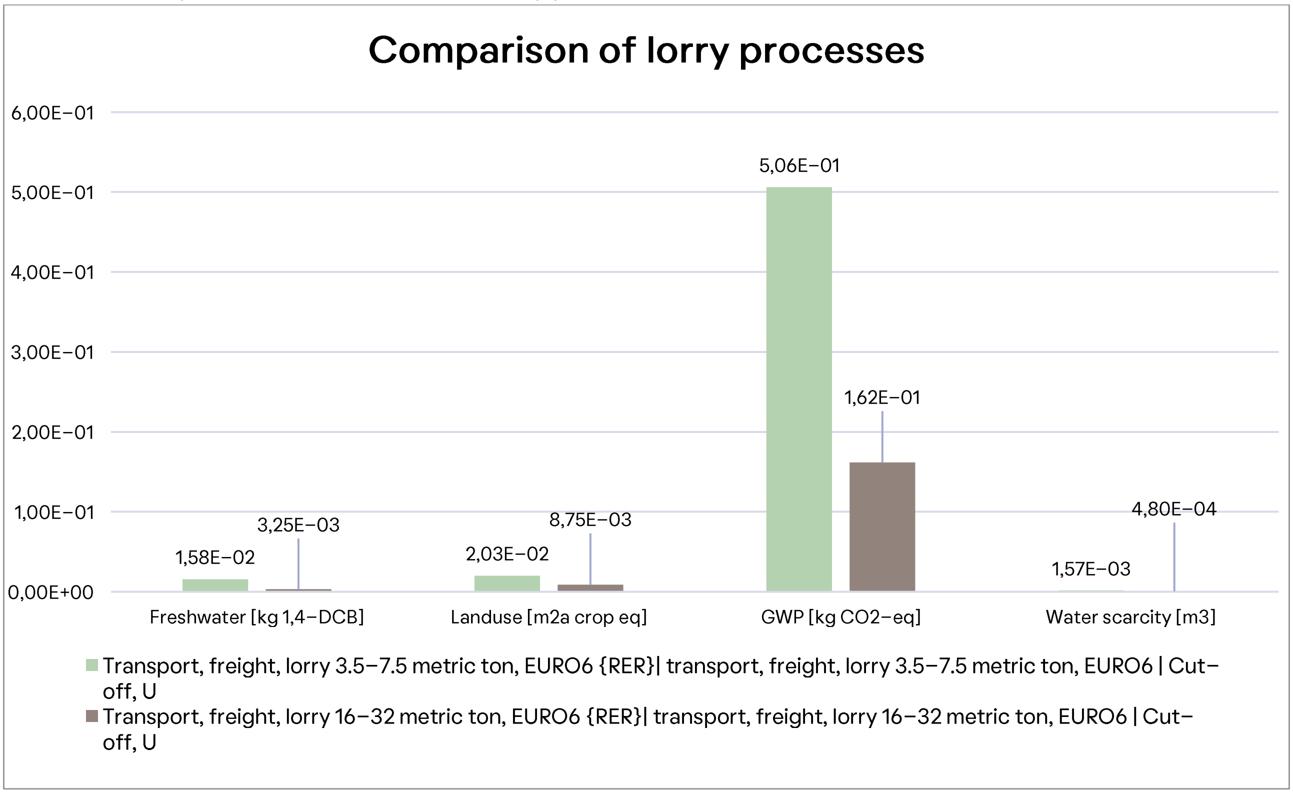

Figure 6.52: Comparison of 3.5–7.5 metric ton, and 16–12 metric ton lorry processes

From the graph above it is evident that the 16–32 ton lorry has a smaller impact in all impact categories than the 3.5–7.5 metric ton lorry. This could be because the larger lorries benefit from the advantages of size, such as having bigger, more fuel-efficient engines and the ability to carry a greater number of items. It is found fair that a 3,5–7,5 ton lorry is used for the modeling of the T-shirt, due to the amount of goods for transportation from Son of a Tailor, the distance travelled, and the type of item being transported. It can also be concluded that choosing the smaller lorry is the more conservative choice, and the right choice when there is no knowledge of which exact type of lorry is used for transportation.

6.2.2 End-of-life scenarios used T-shirt

As described in section 4.10,2, the end-of-life scenarios are based on waste flows from the top four markets in which Son of a Tailor sells their products. A literature search was conducted, and it was possible to investigate studies on how textiles are mixed into the waste streams for each country. This provided some estimates on how much is recycled, incinerated, and how much ends up in landfills. These numbers where used to create a mix for how the T-shirt is treated in the end-of-life.

How much influence the end-of-life treatment has on the T-shirts impact has also been investigated. The figures below show how much the different waste treatments contribute to the different impact categories. In these figures, the impact of disposal of the used T-shirt is shown. This means that the biobag, hang tag, and box are also included. For example, for the landfill scenario, all textile parts are modelled as going to landfill, while the biobag, hangtag, and box are modelled as being included in the end-of-life mix. In the graph, the mix scenario represents the end-of-life scenario presented in the inventory, and it is there for a baseline comparison.

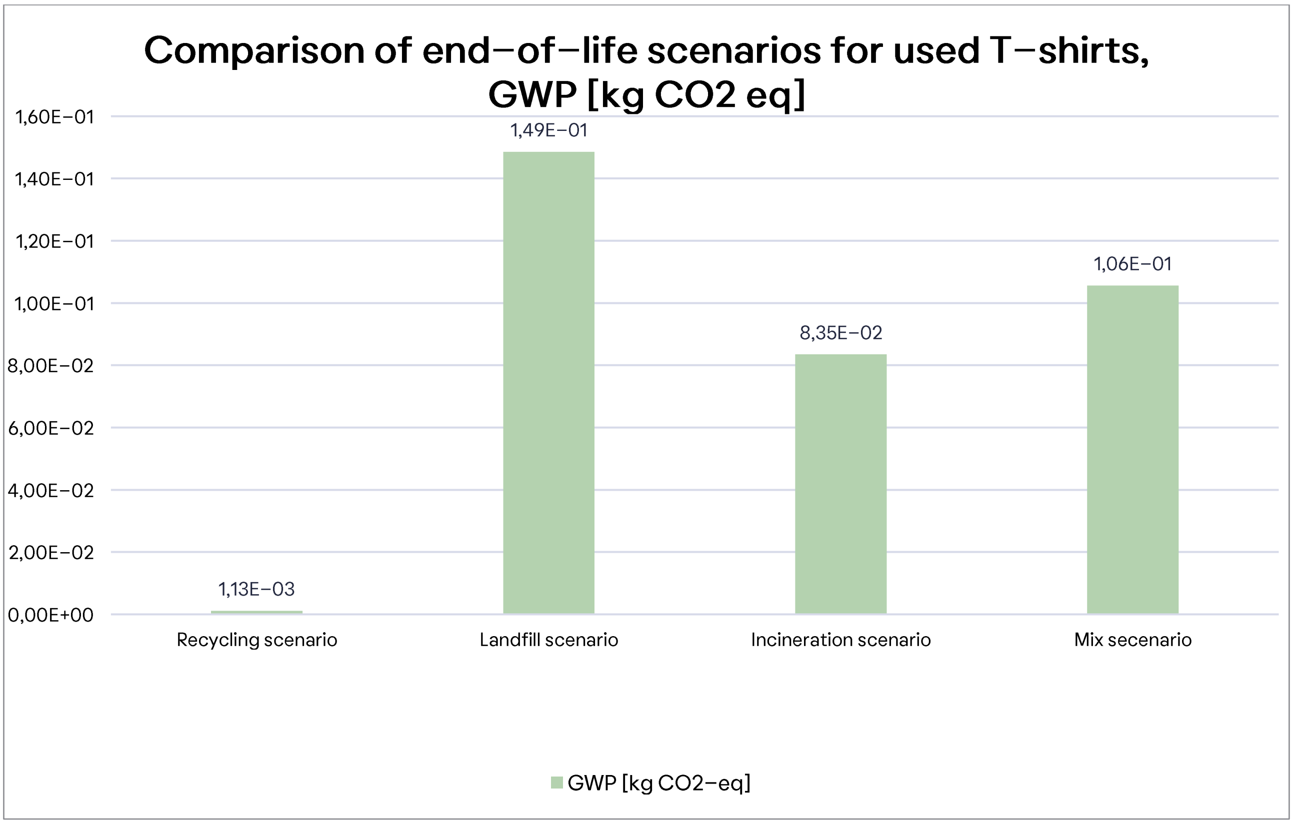

Figure 6.53: Global Warming Potential, end-of-life scenarios.

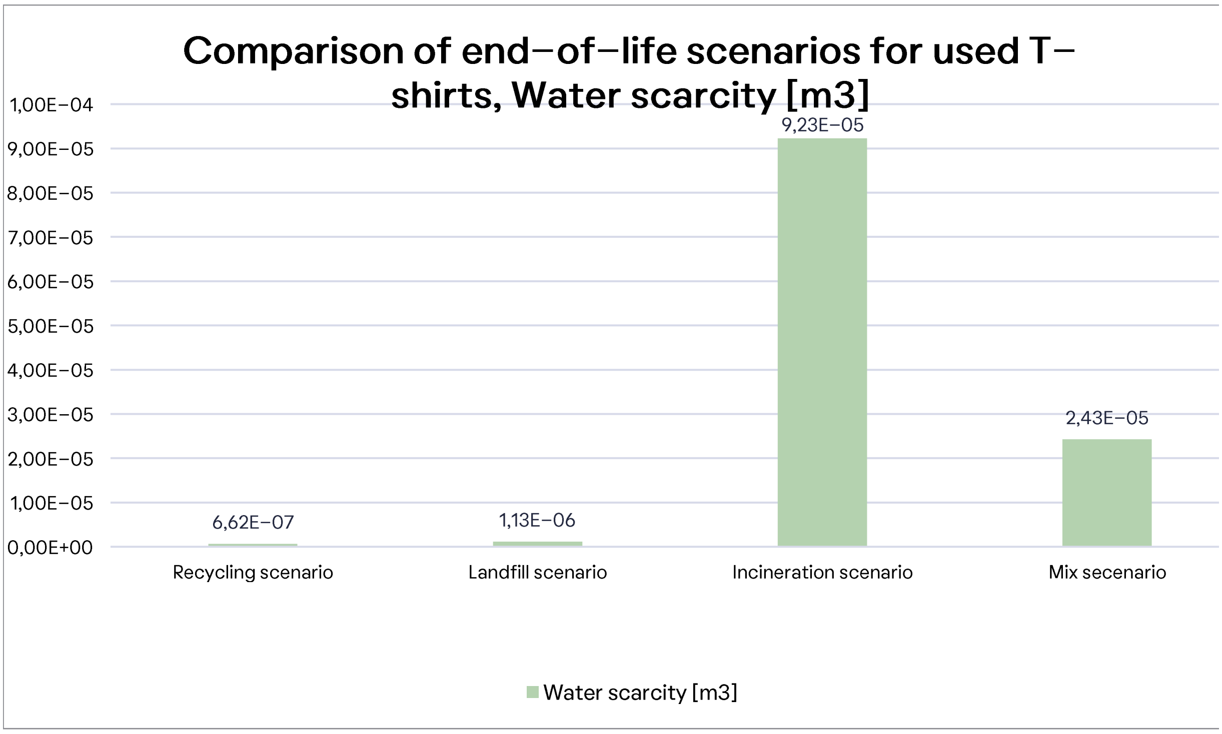

Figure 6.54: Water Scarcity, end-of-life scenarios.

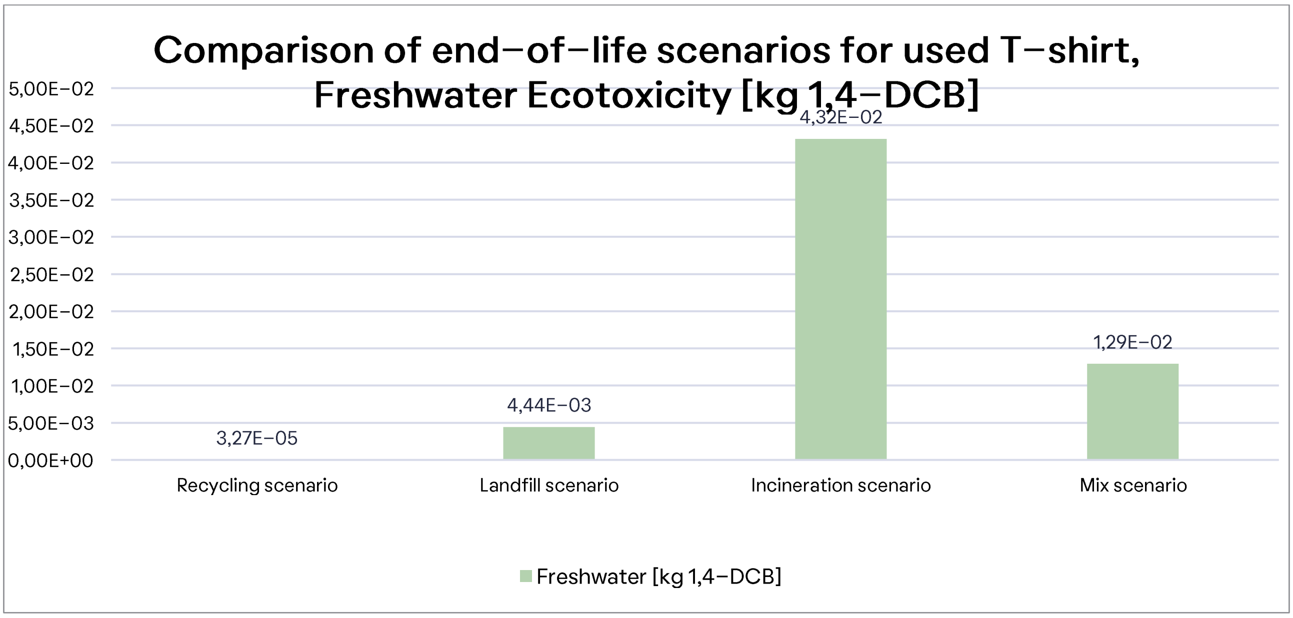

Figure 6.55: Freshwater eco toxicity, end-of-life scenarios.

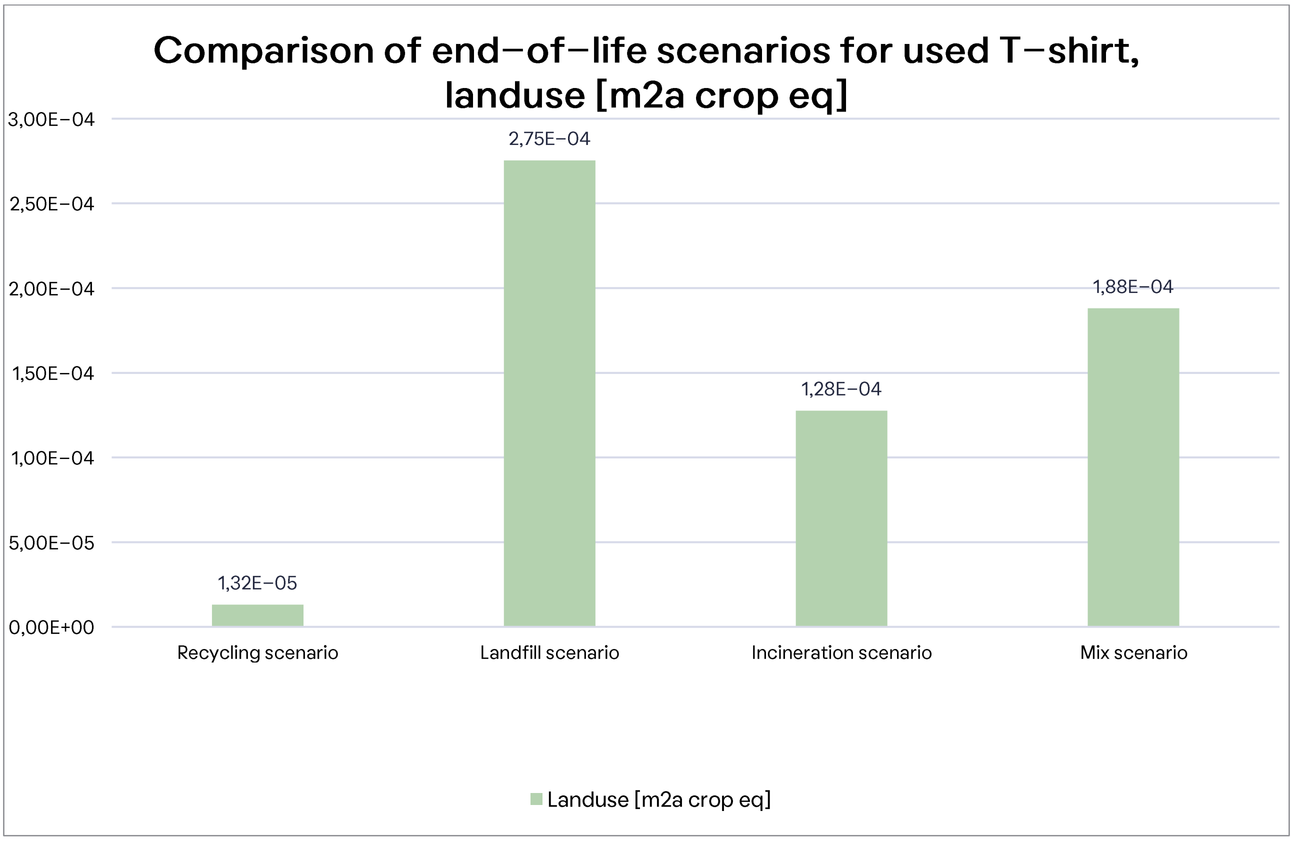

Figure 6.56: Land Use, end-of-life scenarios

As shown in the graphs above, the end-of-life scenario the T-shirt ends up in has great influence on the impact categories in the end-of-life phase.

In the Global Warming Potential category, the difference between the highest contributing scenario (landfill) and the least contributing scenario (recycling) is 0,147kg CO_2e. This means that if the T–shirt in the MTO business model was only sent to landfill, the total global warming potential from cradle to gate would be 3,39 kg CO_2e which would only be an increase in percentage of 1% compared to the current 3,35 kg CO_2e.

However, if the T–shirt in the MTO business model was only recycled, the total impact from cradle to grave in the MTO business model in Global Warming Potential would be a 0,106kg CO_2e decrease, or about 3%, compared to the current 3,35 kg CO_2e. This is of course affected by the chosen allocation method which greatly affects the impact from recycling.

In the Water Scarcity category, the highest impact comes from the incineration scenario, while the lowest impact is in the recycling scenario. If the T–shirt in the MTO business model was only sent to incineration, the total impact on the Water Scarcity category would be 0,127m^3 compared to the current 0,127 m^3, which is a 0,05% increase. If the T–shirt was only sent to recycling, the total impact in this impact category would be 0,127 m^3, a decrease of about 0,02% – which is a very minute difference.

In the Freshwater Ecotoxicity category, incineration is the scenario that contributes the most, and again recycling is the least polluting. This means that if the MTO T–shirt is sent to incineration, the total impact is 0,199 kg 1,4–DCB. That is an increase of 18% compared to the current 0,168 kg 1,4–DCB. If the T–shirt would only be sent to recycling, the total impact cradle to grave would be 0,156 kg 1,4–DCB which is a reduction of 8% compared to the current 0,169kg 1,4–DCB.

In the Land Use category, the biggest impact is in the landfill scenario, while the lowest impact is seen from the recycling scenario. If the MTO T–shirt was only sent to landfill, the total impact in the Land Use category would be 0,01% bigger compared to the current 0,990 m2. If the T–shirt was sent to recycling, there would be a 0,02% decrease in the total impact cradle to grave for the T–shirt.

Overall, it can be concluded that other waste treatment scenarios for the use phase would have a minor effect on the impact categories Global Warming Potential, Water Scarcity, and Land Use. However, there is a potential of an 18% increase in the total Freshwater Ecotoxicity impact of the T–shirt in a cradle–to–grave perspective if all T–shirts were sent to incineration, as well a potential 8% decrease in the cradle–to–grave perspective if they were sent to recycling. However, the end of life for a used T–shirt will eventually be a mix, and not only one single waste treatment. The current model is based on relevant literature for the four countries and is evaluated as being reasonable for the LCA study.

6.2.3 End–of–life scenario for the returned items for MP

As described in section 4.11.9, 30% of production in the MP business model is assessed to be returned items going back to the producer. From there it is estimated that the returned items will eventually be waste treated. Because of low transparency in the industry, an equal distribution between landfill, incineration and recycling has been modeled for the waste treatment for the returned items in the end–of–life return rates mix. However, in this section it will be investigated what kind of effect it has on the MP business model if the best and worst scenario were the case, and how it will reflect on the difference between the MTO and MP business model.

In the four tables below, the differences between the current waste treatment mix for the return rates (divided equally between, landfill, incineration, and recycling), and if 100% of the returned items goes to either incineration, landfill, or recycling is shown.

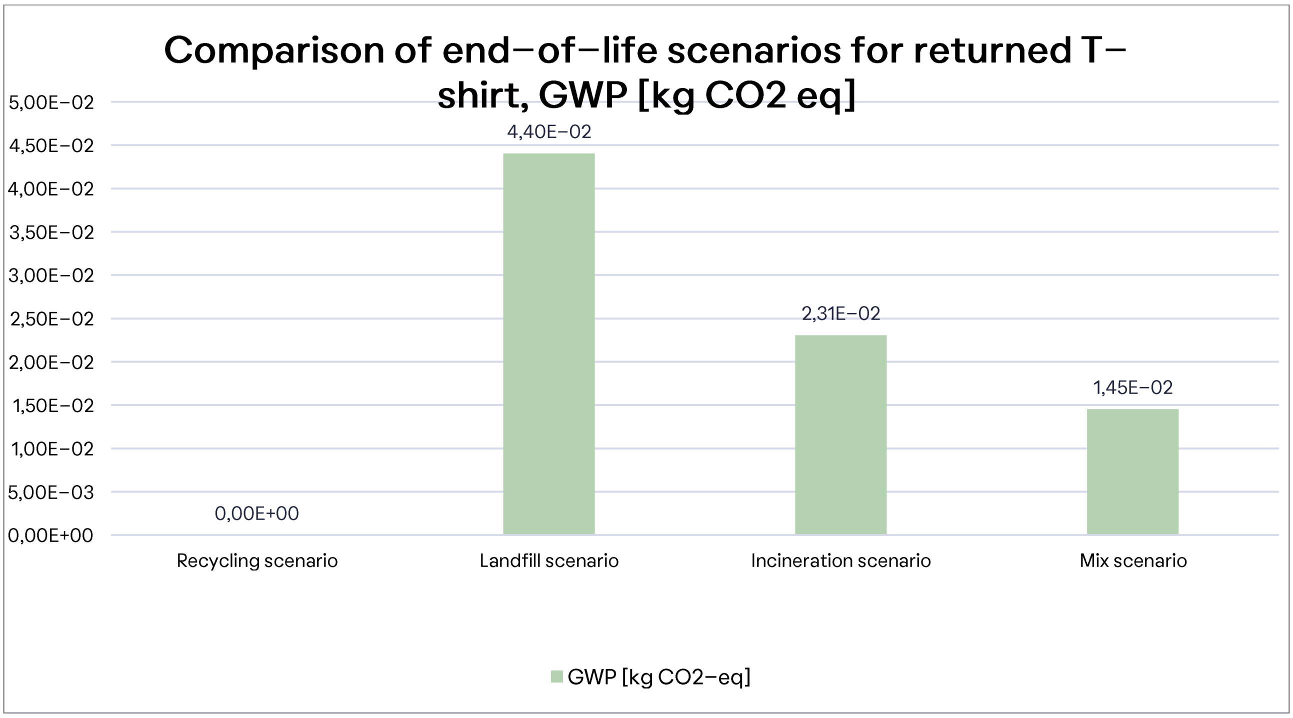

Figure 6.57: Global Warming Potential, end–of–life scenarios only return rates

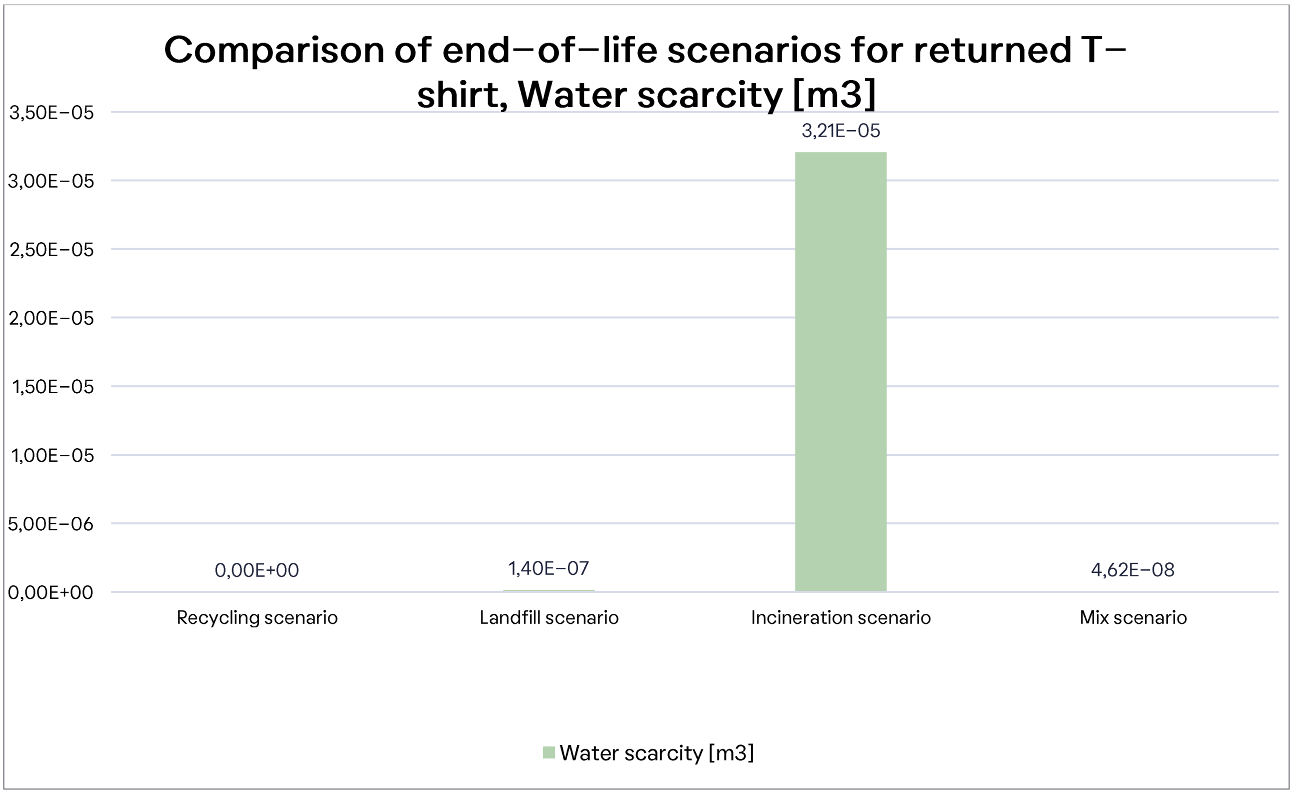

Figure 6.58: Water Scarcity, end–of–life scenarios only return rates

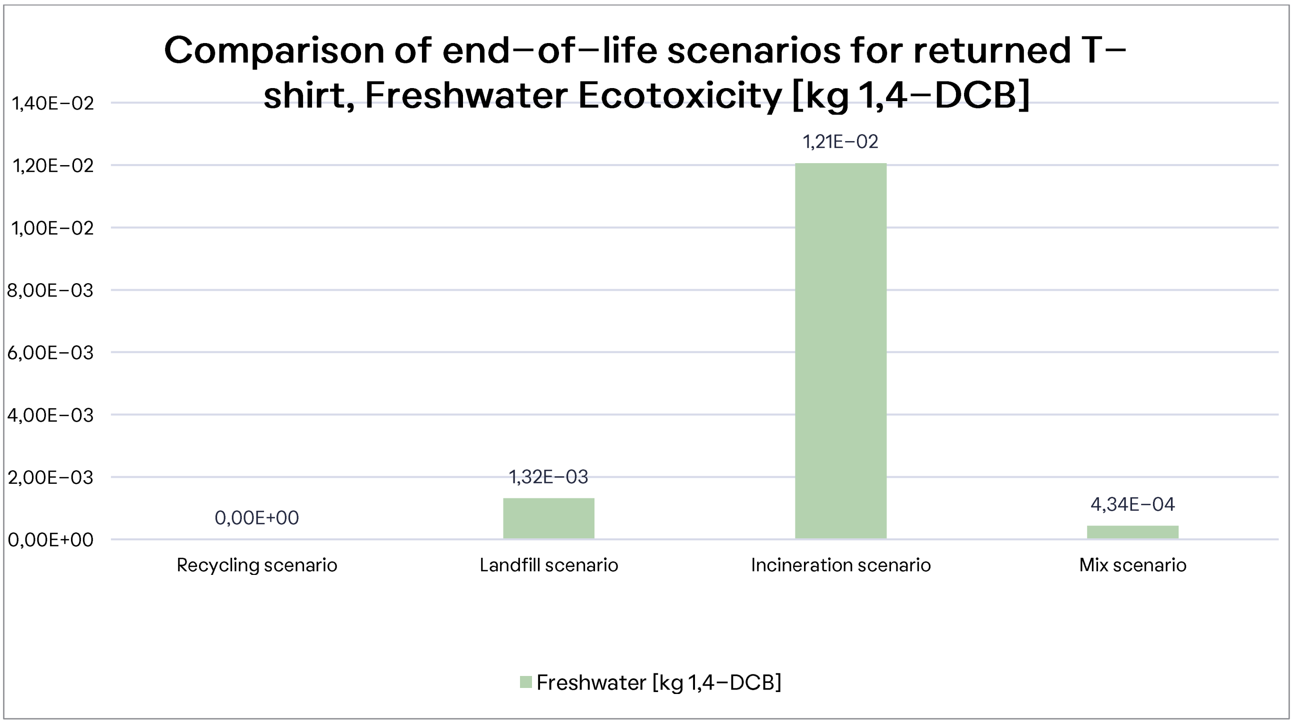

Figure 6.59: Freshwater Ecotoxicity, end–of–life scenarios only return rates

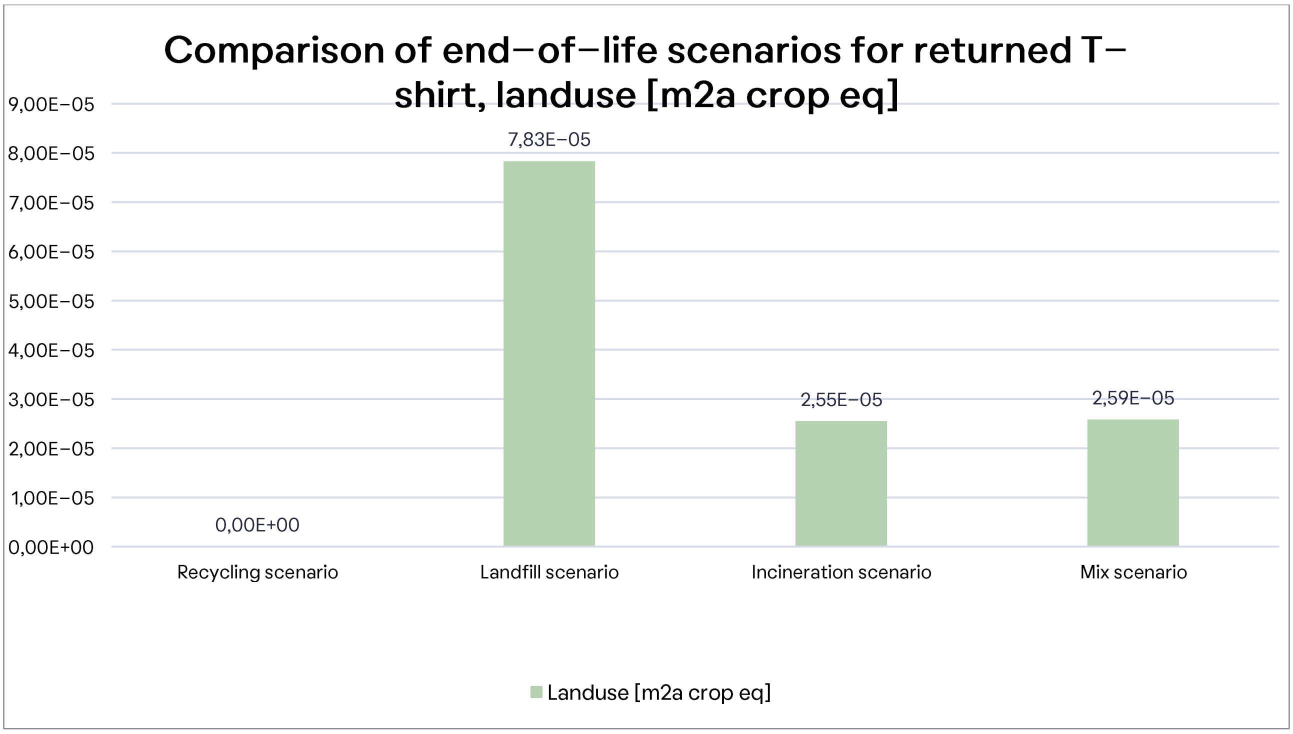

Figure 6.60: Land Use, end–of–life scenarios only return rates

If we look at the full life cycle of the product in MP business model, but with the different scenarios for the return rates in the end–of–life treatment, some interesting indications of the effect is the result. An overview of the percentages is present in table 6.1.

Difference in percentage between MP worst and MP original mix for return rates (cradle–to–grave) in the different impact categories	Global Warming Potential	Water Scarcity	Freshwater Ecotoxicity	Land Use
Percentage	1%	0%	5%	0%

Table 6.1: Differences in percentage between MP worst case and MP original case for returned items.

In the Global Warming Potential category, when we compare the MP worst case for return rates with the original EOL–scenario (mix scenario) from cradle–to–grave, we see only a difference of 1 %. This means that in the overall life cycle of the product in the MP business model, the waste treatment of return rates does not have much effect in the Global Warming Potential category.

In the Water Scarcity potential category, when we compare the MP worst case for return rates with the original EOL–scenario (mix scenario) for return rates from cradle–to–grave, we see there is a difference of about 5%, which is a rather small influence and potential for how the return rates are treated in the end–of–life phase.

In the Freshwater Ecotoxicity category, when we compare the MP worst case for return rates with the original EOL–scenario (mix scenario) for return rates from cradle–to–grave, we see a difference of 5%. This again is a rather large influence and potential for how the return rates are treated in the end–of–life phase.

In the Land Use category, when we compare the MP worst case for return rates with MP best case for return rates from cradle–to–grave, we see a difference of about 0%. This is of course not a significant difference.

T**he best case** scenario would be recycling, since no impact is allocated to Son of a Tailor in this scenario. This is caused by the allocation procedures, which mirror that of the cut–off version of the Ecoinvent database. Therefore, it is reasonable to say that this best case scenario will look different with different allocation procedures.

6.2.4 Method analysis

6.2.4.1 Analysis of water footprint method

Water footprint can be measured by using several different methods. In order to ensure that the conclusions are not impacted by the choice of method, other water footprint methods than Water Scarcity (Berger et. Al, 2014) have been investigated.

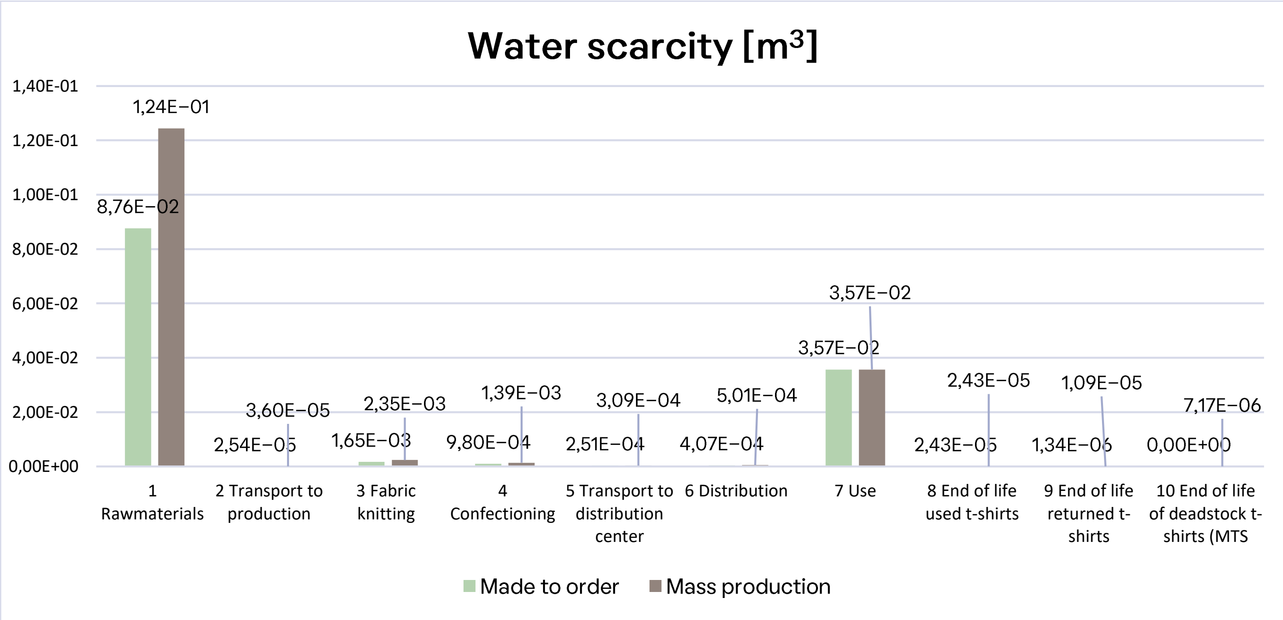

Figure 6.61: Cradle to grave, water scarcity

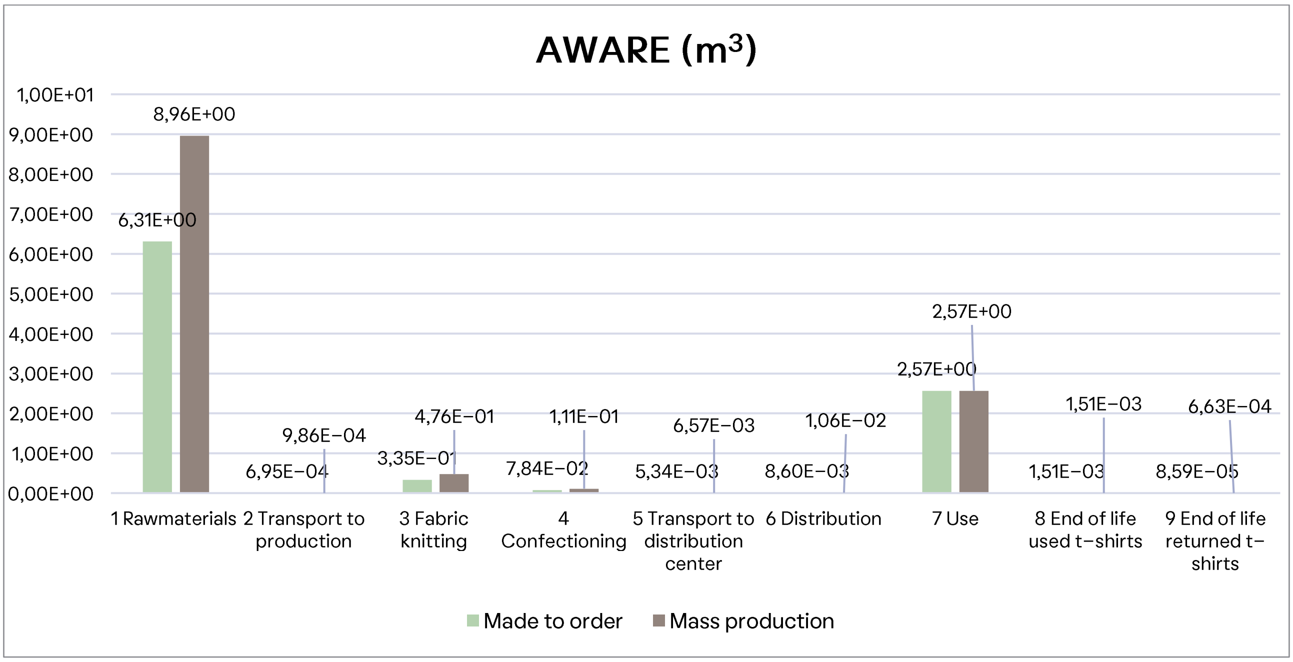

Figure 6.62: Cradle to grave AWARE

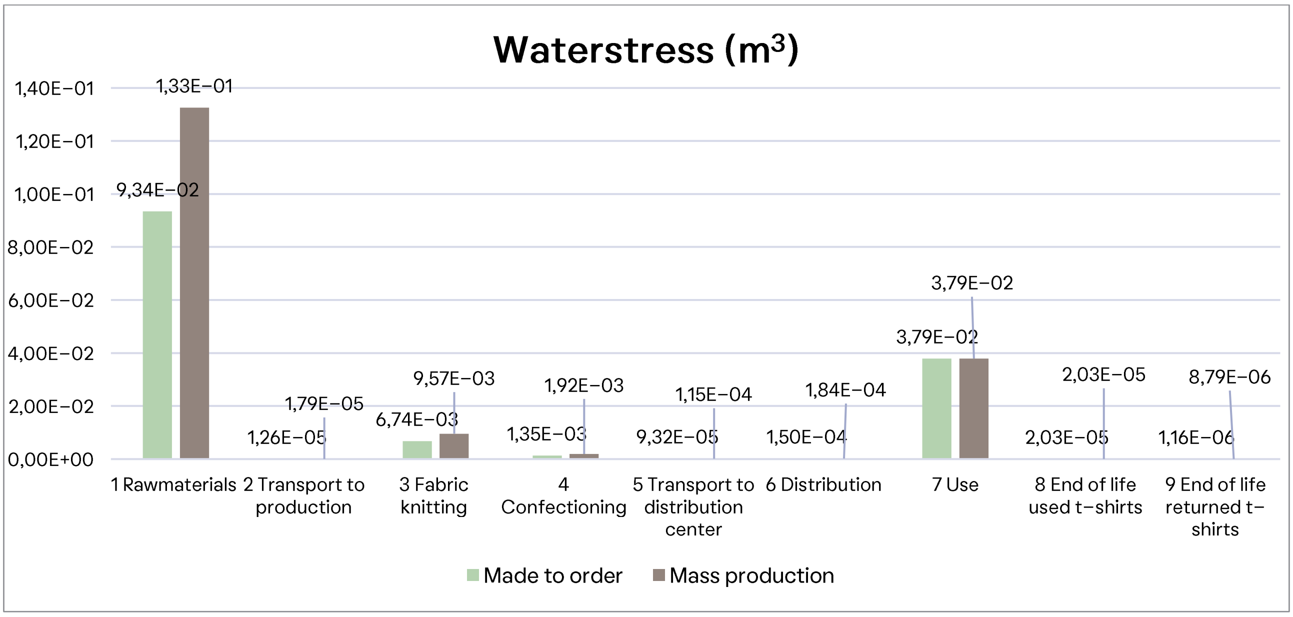

Figure 6.63: Cradle to grave, waterstress

It is shown in the graphs above that the pattern in distribution of impact is the same for all three methods. In addition to this, the impact in m^3 varies between the three methods. However, the methods cannot necessarily be directly compared since they focus on different parameters. AWARE is a regionalized midpoint indicator, which assesses impacts based on availability compared to demand in the geographic location. Water scarcity based on water stress (Boulay et al. 2011) indicates the consumption to availability ratio based on a logistic function which fits the resulting indicator of a value between 0 and $1m^3$. Water scarcity, or WAVE (Berger et al. 2014), is a method that analyzes the vulnerability of water basins to the depletion of freshwater, by relating annual water consumption to the availability in an estimate on 11000 basins. Thus, AWARE focuses on a regionalized midpoint category, and water stress indicates a ratio, while water scarcity indicates vulnerability to water depletion.

It can be concluded that the methods are not directly comparable due to their difference in characterization. Additionally, it can be concluded that the pattern of distribution of impacts is similar enough in all categories that the conclusions will not change based on the choice of method.

6.2.4.2 Analysis of ecotoxicity method

Ecotoxicity can be measured by using several different methods. In order to secure that the conclusions are not impacted by the choice of method, Ecotoxicity freshwater from EF 3.0 method has been compared to the Freshwater Ecotoxicity from ReCiPe.

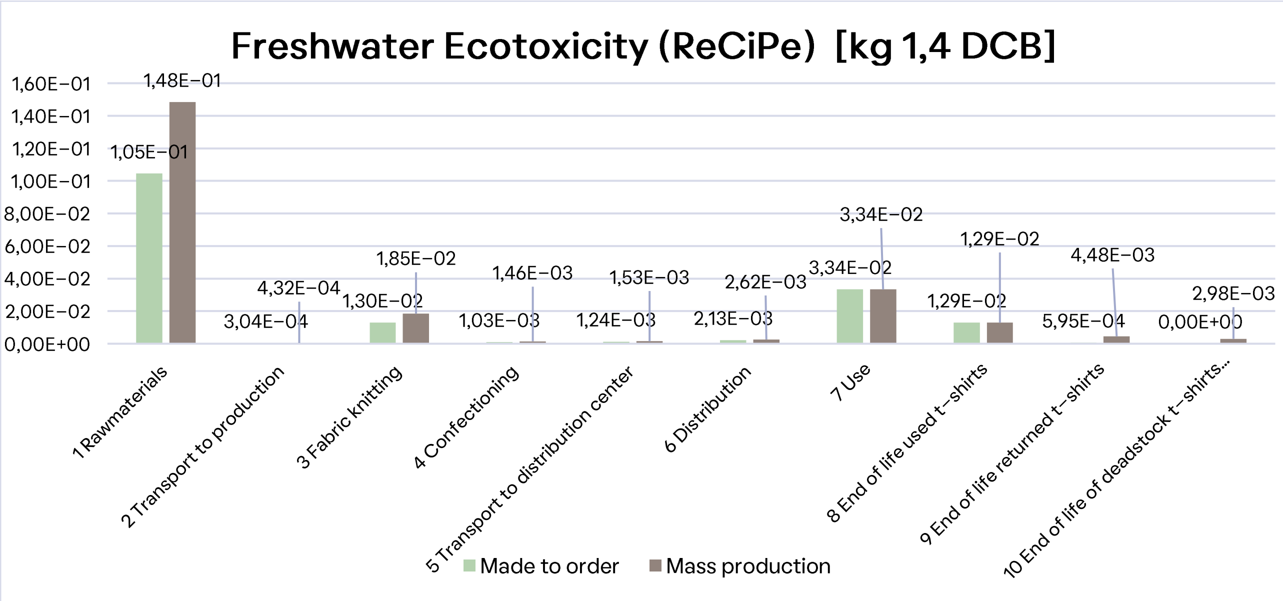

Figure 6.64: Cradle to grave, freshwater ecotoxicity

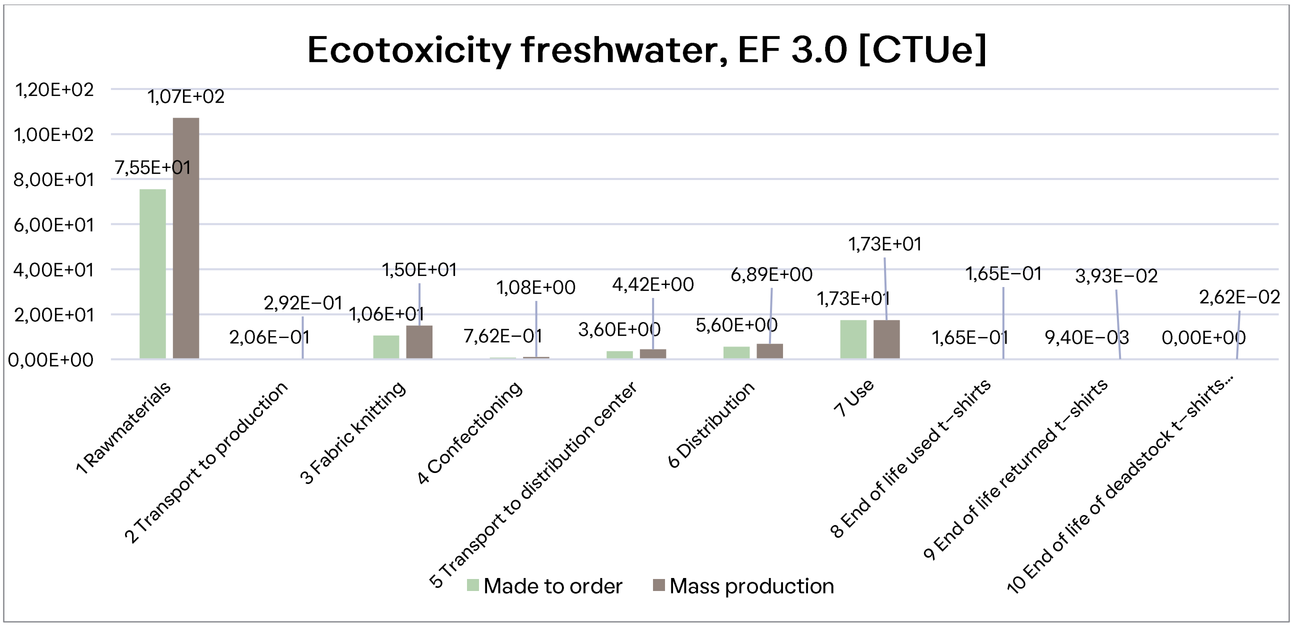

Figure 6.65: Cradle to grave, ecotoxicity freshwater EF 3.0

From the graphs above it is evident that there is no difference in the pattern of the two impact methods. This means that the conclusions drawn from them would be the same. In addition to this it is important to notice the methods use two different units, meaning that the impacts are not directly comparable.

6.3 ASSUMPTIONS AND LIMITATIONS

This LCA Study has been based on primary data from Son of a Tailor's production in Portugal, and from their suppliers in the fabric knitting phase, confectioning phase as well as transportation to distribution center and distribution itself. This is also considered to be the foreground system of the study. The production facility also produces items for other companies, but they were able to allocate 24% of the data to be specific for Son of a Tailor. During the data collection and research there was a lack of access to data about what happens prior to the fabric knitting phase (extraction and premanufacturing of raw materials, upstream transportation), even though Son of a Tailor tried to uncover it from their suppliers. This is considered to be the background system of the study.

Here, as much data as possible was uncovered, but not without limitations. The data on the raw material, being Supima cotton, is based on a secondary data set from Ecoinvent 3.8 database, but with modifications to the heat and electricity mix, making it only representative of the US, since Supima is only produced there. In the use phase and end–of–life phase, limitations and assumptions were also present. The use phase is generally hard to model in LCA studies of products due to lack of knowledge on how users are using the products. For this study, the use phase revolved around determining the input for how many washing cycles a T–shirt with Supima cotton can resist, since the wearing of a T–shirt does not have any environmental impacts. For the washing cycle, a study that determines that a standard cotton T–shirt can resist 17,3 washes before discarded was chosen, and since Son of a Tailor has proof that their T–shirt is 50% more resistant than normal cotton (see Appendix 1), the number of washing cycles was increased by 50%. For data on water use, detergent and electricity, different sources of literature were studied to determine an average. However, since we know the distribution of customers in each country from Son of a Tailor's data, the electricity was modified to match these markets with a weighted percentage. For the detergent, the most sold detergent worldwide was used to represent the average consumer.

The study attempts to compare two different business model, a MTO business model and a MP business model, in relation to Son of a Tailor's production and supply chain. It is important to acknowledge that the precision of data behind the two compared business models is not the same. The MTO business model is, for the most part, based on data from Son of a Tailor and their suppliers, as described above. This means that the baseline for the study is representative of their business only. Therefore, the MP business model is not representative of all companies who do Mass Production, but only representative of a hypothetical scenario in which Son of a Tailor would be producing in a MP business model. It is however representative of the influence that these types of business models have on the carbon footprint of a Son of a Tailor T–shirt. The study results are also very sensitive to the chosen deadstock and return rates since these are the basis for the MP business model. An exact average number for both deadstock and return rates is hard to obtain, since it varies from business to business, but it is recognized in the industry that both deadstock and return rates are a problem. Different types of literature for these numbers have been critically searched to ensure that the numbers chosen were the best available and backed up with quality data. Hence, the 20% for deadstock and 30% for return rates were chosen. Furthermore, transparency in the Apparel and Textile industry is generally considered to be low but is especially so in areas like deadstock values and waste treatment of returned items. Further the study can only say how a Supima cotton T–shirt performs in either a MTO or MP business model related to Son of a Tailor's production, not how it would perform if it was another company's production. Therefor the MTO and MP business models cannot be compared on a general level but only specific to Son of a Tailor.

For further information about limitations and assumptions such as cut off criteria during the LCA study is explained under the section *4.1 Data quality and description.*

6.4 DATA QUALITY ASSESSMENT

Both primary and secondary data for the LCA study has been assessed by the data quality criteria Technology, Geography, Time, and Reliability inspired by the guidelines from the EPD framework. All processes are assessed to be mainly 'good' according to how well they represent the actual process or activity. Secondary data are mainly based on Ecoinvent 3.8, a less than 10–year–old source. The data quality assessment of primary and secondary data can be found in Appendix 3.

6.5 TRANSPARENCY

During the LCA study, all primary data has been gathered with the support of the LCA consultants with weekly data collection meetings. During the data collection meetings, all data was double checked with Son of a Tailor to ensure the use of correct data sources. Both the collected data and the input data to the LCA are accessible and transparent. Raw data from the data collection of Son of a Tailor and input data for the LCA Study can be found in Appendix 2 and 5.

6.6 CONCLUSION

The objective of this LCA study has been to compare the environmental performance of Son of a Tailor's MTO business model with a MP business model and to calculate the baseline for Son of Tailor's Supima cotton T–shirt in a cradle–to–grave perspective. In relation to these objectives and the study overall, the following can be concluded:

- The MP business model has an increased environmental impact in relation to the MTO business model in all of the calculated impact categories.
- With 20% deadstock and 30% return rates in the MP business model, the increase in environmental impact is 33,97% in the Freshwater Ecotoxicity category, 40,36% in the Land Use category, 29,66% in the Global Warming Potential category and 30,01% in the Water Scarcity category when compared the MTO business model.
- With 20% deadstock and 30% return rates in the MP business model, by adhering to a MTO business model, Son of a Tailor can reduce 0,056 1,4 kg DCB in the Freshwater Ecotoxicity category, 0,4m2 crop eq in the Land Use category, 0,99 kg CO2–eq in the Global Warming Potential category and 0,038 m3 in the Water Scarcity category per T–shirt.
- The Made–to–Order model results in lower impacts in all the modelled impact categories. When compared to a Mass Production model, The Made–to–Order model shows a reduction of 22,88% in Global Warming Potential, 23,08% in Water Scarcity, 25,36% in Freshwater Ecotoxicity, and 28,75% in Land Use when considering the entire product lifecycle.
- The MTO business model will have a smaller environmental impact than the MP business model even if the deadstock waste and return rates percentages are lower.
- The raw material phase is the most contributing in all impact categories in both the MTO and MP business model.
- The distribution phase has a high impact in the Global Warming Potential category due to the use of aircraft as mode of transport.

- The high use of natural gas in the dyeing and finishing process is the main reason for environmental impact contribution in the fabric knitting phase.
- The baseline in a cradle–to–grave perspective for the Supima cotton T–shirt in the MTO business model are 0,17 1,4 kg DCB in the Freshwater Ecotoxicity category, 0,99 m2 crop eq in the Land Use category, 3,35 kg CO2 eq in the Global Warming Potential category and 0,127 m3 in the Water Scarcity category.

6.7 RECOMMENDATION

The following sections presents a set of recommendations that Son of a Tailor could follow, enabling them to optimize the environmental impact of their Supima cotton T–shirt. The recommendations are as follows:

- Engage with the supplier who is responsible for the dyeing and knitting and investigate the possibilities of either lowering the amount of natural gas used, or alternatively switching to another more renewable energy source.
- Investigate whether transport by aircraft can be replaced in the distribution phase, I.e., by lorry shipment.
- Organic cotton might have less environmental impact per kg in three of the four impact categories, which could improve impact of the raw material phase, but it is important to notice that the reference flow for organic cotton might be higher, since the organic cotton does not have the same technical performance as Supima cotton. Therefore, in relation to the functional unit a higher reference flow might be needed and the benefits in the impact categories will therefore be minor or non–existing.
- It is recommended to keep tracking on the different data points collected in tier 1 and tier 2 if future LCAs are desired.
- The use of tumble dryer in the use phase will significantly increase the impact of the T–shirt in the Global Warming Potential and Fresh water ecotoxicity impact categories. Therefore, it is recommended to continue or improve the communication efforts creating user awareness of the importance of not using a tumble dryer after washing.

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8 CRITICAL REVIEW STATEMENT

Review statement for Life Cycle Analysis of a Supima Cotton T–shirt

Review conducted by:

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2.–0 LCA consultants

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The reviewed LCA study is a thorough analysis of the impact from the production, use and end–of–life of a Supima cotton T–shirts. The LCA study clearly shows the environmental importance of a flow return rate and textile waste, as it has a direct influence in terms of reducing the amount of cotton used in order to provide one wearable T–shirt to a costumer, which results in a lower environmental impact.

The LCA report describes clearly how the business model of made–to–order (MTO) for the Supima cotton T–shirt is compared to a generic mass–production (MP) of a cotton T–shirt, and it is thus ensured that the two systems are equivalent in terms of function. The data quality of the MP system is lower than the MTO system since Son of a Tailor can only provide specific primary data for the MTO business model. Nevertheless, this concern is not expected to change the conclusion of the study. Overall, the applied inventory data is considered satisfactory, and the study is deemed valid and robust.

If the study should be updated in the future, it is recommended that the more specific data is applied for the MP system in order to heighten the robustness of the LCA model. Moreover, additional impact categories could be of importance, e.g., indirect land–use changes due to the cultivation of cotton as well as ecotoxicity and human toxicity, as this is linked to the significant use of pesticides in cotton production.

9 CRITICAL REVIEW COMMENTS

1st and 2nd round of review of life cycle assessment of a supima cotton T-shirt – comparison between a made-to-order and a mass production business model

1st round of feedback

Item #	Topic	Source	Item description	Requirement or recommendation?	Has the requirement/recommendation been met?	Technical comments from the reviewer, if applicable	General comments from the reviewer, if applicable	Response to the comment by the author of the LCA study, if applicable	2nd response from reviewer
1	General	ISO 14044:2006, section 4.1	LCA studies shall include definition of goal and scope, inventory analysis, impact assessment and interpretation of results	Requirement		Include a sentence or two that define what the goal chapter and the scope chapter each describe		A sentence of this has been included	OK
2	General	ISO 14044:2006, section 4.1	LCI studies shall include definition of goal and scope, inventory analysis and interpretation of results	Requirement		Include a sentence or two that define what the goal chapter and the scope chapter each describe		A sentence of this has been included	OK
3	Public comparative assertions	ISO 14044:2006, section 4.1	An LCI study alone shall not be used for comparisons intended to be used in comparative assertions intended to be disclosed to the public.	Requirement	Requirement met	OK			
4	Goal and scope	ISO 14044:2006, section 4.2	The goal and scope of an LCA shall be clearly defined and	Requirement	Requirement met	OK			

			consistent with the intended application.						
5	Goal and scope	ISO 14040:206 6, section 5.2	The scope should be sufficiently well defined to ensure that the breadth, depth and detail of the study are compatible and sufficient to address the stated goal.	Recommendatio n	Requirement met	OK			
6	Goal and scope	ISO 14044:200 6, section 4.2	In defining the goal of an LCA, the intended application shall be unambiguously stated.	Requirement	Requirement met	OK			
8	Goal and scope	ISO 14044:200 6, section 4.2	In defining the goal of an LCA, the intended audience, i.e., to whom the results of the study are intended to be communicated shall be unambiguously stated.	Requirement	Requirement met	OK			
9	Public comparative assertions	ISO 14044:200 6, section 4.2	In defining the goal of an LCA, whether the results are intended to be used in comparative assertions	Requirement	Requirement met	OK			

			intended to be disclosed to the public shall be unambiguously stated.						
10	Goal and scope	ISO 14044:2006, section 4.2	In defining the scope of an LCA, the product system to be studied shall be considered and clearly described.	Requirement		Most of the product system is understandable, but some things are unclear. The understanding could be improved by making figures more detailed. Specifically, it could be good to explain why the EoL of returns is not the same in MP and MTO. Moreover, it could be good to show, where in the life cycle that different materials are sent to waste management (e.g., when packaging is sent to waste management and when cotton/fabric/T-shirts are sent to waste management).	Figure 3.1 could be improved if it showed a link/arrow between raw materials and production and if it was made clean which life cycle stages the cardboard, biobag and recycled polyester satin went through. Could also be an idea to make it more clean which raw materials are used for the t-shirt and the packaging. And End of life for the waste could also be included. Moreover, it could improve the understanding of the product system, if there were two versions for each scenario, where the differences between them were clearly seen (e.g., the difference in waste fabric). We recommend updating figure 4.1 as well focusing on	The product system has been updated with more details and has been split into two figures. One for the MTO and one for the MP. This gives the reader a clearer understanding of the differences between the two models. Section 4.2 has been updated to provide a clearer understanding of the differences. Updates in section 4.10 has also been made to accommodate this.	OK

							the feedback above. Note, in section 4.2, it is stated that the EoL of MP returned clothes are equal distributed between recycling, landfill and incineration, while the EoL of MTO returns are "discarded". Is that the same EoL? It is cleared up in section 4.11.8 but the wording in section 4.2. is a bit confusing.		
11	Goal and scope	ISO 14044:2006, section 4.2	In defining the scope of an LCA, the function(s) and functional unit shall be considered and clearly described.	Requirement		The functional unit could be more clearly defined, e.g., the function of a T-shirt is not to be produced but to be used, so a suggestion would be to remove the production from the functional unit definition. Moreover, the function of a T-shirt is not to be of Supima cotton but to ensure use XX number of times and XX		The functional unit has been updated see section 3.1	OK

						number of washes - the Supima cotton quality may be able to deliver this function 1:1 while a T-shirt of lower quality can deliver this function 1:2 (an example). We recommend that you adjust to reference flow according to the changes made in the functional unit.			
12	Goal and scope	ISO 14044:2006, section 4.2	The scope of an LCA shall clearly specify the functions (performance characteristics) of the system being studied.	Requirement		See item 11		Functional unit has been updated see section 3.1	OK
13	Goal and scope	ISO 14044:2006, section 4.2	The functional unit shall be consistent with the goal and scope of the study and shall be clearly defined and measurable.	Requirement	Requirement met	OK			
14	Comparative LCA	ISO 14044:2006, section 4.2	Comparisons between systems shall be made on the basis of the same function(s), quantified by the same functional	Requirement	Requirement met	OK			

			unit(s) in the form of their reference flows. If additional functions of any of the systems are not taken into account in the comparison of functional units, then these omissions shall be explained and documented.						
15	Goal and scope	ISO 14044:2006, section 4.2	In defining the scope of an LCA, the system boundary shall be considered and clearly described.	Requirement	Requirement met	OK			
16	Goal and scope	ISO 14044:2006, section 4.2	The system should be described in sufficient detail and clarity to allow another practitioner to duplicate the inventory analysis.	Recommendation	Requirement met	OK	Appendix 5 gives a nice overview, but the colour coding it a bit confusing. Why are some background activities coloured different shade of green? And why are there no background activities in the tables without values, e.g., for electricity inputs for "yarn, cotton" and "fibre, cotton"? Moreover, it would improve the understanding and other practitioners'	Appendix 5 has been updated with correct colour coding. A flowchart from Simapro has been made from both systems to visualize the flows and the inputs and outputs. Reference flow data from appendix 5 has been added in the inventory for both MTO	OK

							possibility of reproducing the results if the tables from appendix 5, which includes inputs to a specific reference flow was included in the report. We recommend making a flowchart to show the two overall systems and how each activity is linked in SimaPro in order to make the LCA study structure more transparent. Moreover, we recommend including the tables from sheet "Inputs MTO" and "Inputs MP" from appendix 5 in the report, since it shows the reference flow for each activity and the link to background processes.	and the MP model.	
17	Goal and scope	ISO 14044:2006, section 4.2	The selection of the system boundary shall be consistent with the goal of the study.	Requirement	Requirement met	OK	We recommend that you highlight why it is important for the study to include the EoL of the T-shirt. At first, we thought that it should be the same in both scenarios, but since Son of a	According to the second goal, which is to calculate a baseline for Son of a Tailor's Supima cotton t-shirt in a cradle to grave perspective, it is	OK

							Tailer does not receive returns, the EoL of the additional 5.7% should be included in the comparison with MP. Thus, it is good that you compare in a cradle-to-grave perspective which we see as an important point of view to present.	relevant to include the EOL for the t-shirt. We have for transparency and for better understanding divided the EOL into multiple phases. Now there is a EOL of used t-shirt (which is identical for both systems) and an end of life of returned t-shirts (which is different in the two systems), and End of life of deadstock t-shirt (which is only applicable for the MP model) Updated description can be seen in section 3.2	
18	Goal and scope	ISO 14044:2006, section 4.2	The criteria used in establishing the system boundary shall be identified and explained.	Requirement	Requirement met	OK			
19	Goal and scope	ISO 14044:2006, section 4.2	The deletion of life cycle stages, processes, inputs or outputs is only permitted if it	Requirement		We recommend explaining why the processes in section 3.3.2 has been		A table with excluded processes in section 3.3.2 has been made	OK

			does not significantly change the overall conclusions of the study. Any decisions to omit life cycle stages, processes, inputs or outputs shall be clearly stated and the reasons and implications for their omission explained.			excluded. Is it due to lack of data? Because it is the same in both scenarios and therefore can be excluded? Moreover, double check if all excluded processes are mentioned. Is the transport by truck from the different states in the US to the port excluded?		with reasoning for exclusion.	
20	Goal and scope	ISO 14044:2006, section 4.2	The cut-off criteria for initial inclusion of inputs and outputs and the assumptions on which the cut-off criteria are established shall be clearly described. The effect of the cut-off criteria selected on the outcome of the study shall also be assessed and described in the final report.	Requirement		Describe the cut-off criteria as well as assess and comment on the effect of the cut-off criteria		Description of cut-off criteria has been made as well as the system modelling. The effect of cut off is described in interpretation section 6.1	OK
21	Goal and scope	ISO 14044:2006, section 4.2	In defining the scope of an LCA, allocation procedures shall	Requirement		The background database is the "cut-off" version of Ecoinvent.		The allocation procedure has been aligned to match the cut-	OK

			be considered and clearly described.			This means that the applied background database uses economic allocation based on the materials classification (allocatable, recyclable or waste). However, the foreground system of this study does not use economic allocation - instead, system expansion is used, e.g., the system includes the waste fabric as a by-product from the T-shirt production. This is a consequential approach for LCA. Moreover, the recycling of cotton at EoL which substitutes new cotton fibres is also a consequential approach. Thus, there is not consistency between the allocation procedures in the study.		off system modelling in Ecoinvent. The waste fabric from production is updated so it is not modeled as a biproduct but follows the polluters pay principle. The benefits from recycling is allocated to the next product system. The allocation procedures is commented on throughout the inventory and is explained in section 4.1.5	

						We recommend aligning allocation procedures. If not, the report should explain the use of different allocation procedures.			
22	Goal and scope	ISO 14044:2006, section 4.2	In defining the scope of an LCA, LCIA methodology and types of impacts shall be considered and clearly described. It shall be determined which impact categories, category indicators and characterization models are included within the LCA study. The selection of impact categories, category indicators and characterization models used in the LCIA methodology shall be consistent with	Requirement	Requirement met	OK	We recommend that you comment on the use of three different LCIA methods and the reasons for it. Especially since ReCiPe also included GWP as an impact category like IPCC (2021)	Comments and reasoning for the chosen impact categories has been made in section 3.2.1 and why different ones have been chosen.	OK

			the goal of the study.						
23	Goal and scope	ISO 14044:2006, section 4.2	In defining the scope of an LCA, the interpretation to be used shall be considered and clearly described.	Requirement	Requirement met	OK			
24	Goal and scope	ISO 14044:2006, section 4.2	In defining the scope of an LCA, data requirements shall be considered and clearly described.	Requirement		Section 4.1 does not include any data quality requirements - it only describes how the data quality was assessed. Please describe data requirements for the LCA study under goal and scope.	A small note: Data or background activities are not from SimaPro; SimaPro is the software and Ecoinvent is the database. We recommend that you go through the report and make sure that you reference SimaPro and Ecoinvent at the right context.	A description of data quality requirements covering geographical, technological and time representative has been made in beginning of section 4.1. Simapro and Ecoinvent is now referenced correctly in the report.	OK
25	Goal and scope	ISO 14044:2006, section 4.2	In defining the scope of an LCA, assumptions shall be considered and clearly described.	Requirement	Requirement met	OK	We recommend to comment on the assumptions in section 3.3.1, e.g., why they have been deemed realistic/reasonable. Especially if the assumptions are different between the two scenarios. Moreover, we recommend that it	A table in section 3.3.1 with assumptions, reasoning and evaluation has been made.	OK

							is assessed which impact the assumption has on the results, e.g., if they are under/overestimated.		
26	Goal and scope	ISO 14044:2006, section 4.2	In defining the scope of an LCA, value choices and optional elements shall be considered and clearly described	Requirement	Requirement met	OK			
27	Goal and scope	ISO 14044:2006, section 4.2	In defining the scope of an LCA, limitations shall be considered and clearly described.	Requirement	Requirement met	OK			
28	Goal and scope	ISO 14044:2006, section 4.2	In defining the scope of an LCA, data quality requirements shall be considered and clearly described. The treatment of missing data shall be documented for each unit process and for each reporting location where missing data are identified.	Requirement		Please describe data requirements for the LCA study under goal and scope. E.g., what the requirements was for the data's time-related, geographical, and technology coverage and so on. See section 4.2.3.6.1 in ISO 14044.		A description of data quality requirements covering geographical, technological and time representatives has been made in section 4.1.	OK
29	Goal and scope	ISO 14044:200	The data quality requirements should address	Recommendation	Requirement met	OK	A small note: Data or background activities are not	Correct references to both SimaPro	OK

		6, section 4.2	time-related, geographical, and technology coverage, precision, completeness, representativeness, consistency, reproducibility, sources of the data, and uncertainty.				from SimaPro; SimaPro is the software and Ecoinvent is the database. We recommend that you go through the report and make sure that you reference SimaPro and Ecoinvent at the right context.	and Ecoinvent has been made.	
30	Goal and scope	ISO 14044:2006, section 4.2	In defining the scope of an LCA, the type of critical review, if applicable, shall be considered and clearly described. Whether and how to conduct a critical review, the type of critical review, as well as who conducts the review and their level of expertise, shall be defined in the scope of the study.	Requirement		Write a sentence or two, where you describe who should do the critical review and define their level of expertise.		A section 2.3.1 has been added describing the critical reviewer and level of expertise.	OK
31	Goal and scope	ISO 14044:2006, section 4.2	In defining the scope of an LCA, the type and format of the report required for the study shall be considered and clearly described.	Requirement		Have one sentence about the type of report required for the LCA study.		A sentence about the type of report has been included in section 3.	

32	Comparative LCA	ISO 14044:2006, section 4.2	In a comparative study, the equivalence of the systems being compared shall be evaluated before interpreting the results. Consequently, the scope of the study shall be defined in such a way that the systems can be compared. Systems shall be compared using the same functional unit and equivalent methodological considerations, such as performance, system boundary, data quality, allocation procedures, decision rules on evaluating inputs and outputs and impact assessment. Any differences between systems regarding these parameters shall be identified and reported.	Requirement		This seems ok we would like to confirm this when points for item 10 have been implemented			OK

33	Life cycle inventory analysis	ISO 14044:2006, section 4.3	For those data that may be significant for the conclusions of the study, details about the relevant data collection process, the time when data have been collected, and further information about data quality indicators shall be referenced.	Requirement	Requirement met	OK	Intro section to chapter 4: We recommend commenting on the 4-month data collection period; it is short/long? Why was this period chosen?	A comment on the data collection period has been made in section 4.	OK
34	Life cycle inventory analysis	ISO 14044:2006, section 4.3	Since data collection may span several reporting locations and published references, measures should be taken to reach uniform and consistent understanding of the product systems to be modelled.	Recommendation	Requirement met	OK			
35	Life cycle inventory analysis	ISO 14040:2006, section 5.3	Practical constraints on data collection, if any, should be considered in the scope and documented in the study report.	Recommendation	Requirement met	OK	We recommend describing if there have been any data collection constraints, e.g., when getting data from tier 1 and tier 2	Description of data collection constraints has been added in section 4.1.	OK

36	Life cycle inventory analysis	ISO 14044:2006, section 4.3	All calculation procedures shall be explicitly documented and the assumptions made shall be clearly stated and explained.	Requirement		It is not clear from the report how the different values have been calculated, e.g., the distribution between waste management types at the End of life for the T-shirt and how the additional percentages have been used to calculate the additional amount of raw materials needed to fulfill the functional unit. Please show calculation procedures in the report.		Calculation procedures and examples has been added throughout the inventory	OK
37	Life cycle inventory analysis	ISO 14044:2006, section 4.3	All calculation procedures should be consistently applied throughout the study.	Recommendation		Background database has a different allocation procedure than what is applied in the foreground system. We recommend to align the allocation procedure between background database and		See previous answer in item 21. Allocation procedure is aligned.	OK

						foreground system or argue for why the difference is necessary.			
38	Life cycle inventory analysis	ISO 14044:2006, section 4.3	Decisions regarding the data to be included, such as life cycle stages, unit processes, and inputs and outputs, shall be based on a sensitivity analysis to determine their significance.	Requirement		We recommend to perform a sensitivity analysis on the most important processes and main assumptions in order to assess if any of the data, life cycle stages, choice of background datasets or similar has a significant impact on the results. This is done a bit for the EoL scenario, but this is not the biggest contributor in the study. We therefore recommend if other value choices have a significant impact on the conclusions.		A sensitivity analysis on the most contributing processes has been conducted. A sensitivity check on the methodology choices has been made.	OK
39	Life cycle inventory analysis	ISO 14044:2006, section 4.3	The inputs and outputs shall be allocated to the different	Requirement		We recommend to state the applied allocation		Allocation procedures has been stated and	OK

			products according to clearly stated procedures that shall be documented and explained together with the allocation procedure.			procedure more clearly and to show calculation procedures in the report.		calculations has been added	
40	Life cycle inventory analysis	ISO 14044:2006, section 4.3	Whenever several alternative allocation procedures seem applicable, a sensitivity analysis shall be conducted to illustrate the consequences of the departure from the selected approach.	Requirement		Background database has a different allocation procedure than what is applied in the foreground system. We recommend to align the allocation procedure between background database and foreground system or argue for why the difference is necessary.		See previous answer in item 21. Allocation procedure is aligned.	OK
41	Life cycle inventory analysis	ISO 14044:2006, section 4.3	The study shall identify the processes shared with other product systems and deal with them according to the stepwise allocation procedure	Requirement		We recommend to state the applied allocation procedure more clearly and to show calculation procedures in the report.		Allocation procedures has been stated and calculations has been added	OK

			described in ISO 14044:2006 section 4.3.4.2. Allocation procedures shall be uniformly applied to similar inputs and outputs of the system under consideration.						
42	Life cycle impact assessment	ISO 14044:2006, section 4.4	The LCIA phase shall take into account possible omissions and sources of uncertainty, particularly whether (1) the quality of the LCI data and results are sufficient to conduct the LCIA in accordance with the study goal and scope definition, (2) the system boundary and data cut-off decisions have been sufficiently reviewed to ensure the availability of LCI results necessary to calculate indicator results for the LCIA, and (3) the environmental relevance of the LCIA results is	Requirement		OK if the previous comments for data cut-off is implemented (e.g., see item 19 and 20)			OK

			decreased due to the LCI functional unit calculation, system wide averaging, aggregation and allocation.						
43	Life cycle impact assessment	ISO 14044:2006, section 4.4	The LCIA phase shall include the selection of impact categories, category indicators and characterization models. For such selection, the following aspects should be observed: (1) the related information and sources shall be referenced, (2) the selection shall be both justified and consistent with the goal and scope of the LCA, (3) The selection of impact categories shall reflect a comprehensive set of environmental issues related to the product system being studied, taking the goal and	Requirement		In order to fulfill this requirement, you should investigate if other impact categories (besides from the 4 selected by Son of a Tailer) are of relevance for the study. The report should include argumentation for the choice of the different impact categories (why the chosen impact categories are important)		Argumentation for selected impact category and investigation of others has been added in section 3.2.1	OK

			scope into consideration, (4) The environmental mechanism and characterization model that relate the LCI results to the category indicator and provide a basis for characterization factors shall be described, and (5) The appropriateness of the characterization model used for deriving the category indicator in the context of the goal and scope of the study shall be described.						
44	Life cycle impact assessment	ISO 14044:2006, section 4.4	For each impact category, the necessary components of the LCIA include: (1) identification of the category endpoint(s), (2) definition of the category indicator for given category endpoint(s), (3) identification of appropriate LCI	Requirement	Requirement met	OK	We recommend that you include a source or a link to where the reader can learn more about the applied LCIA methods.	This has been added in the report under section 3.2.1	OK

			results that can be assigned to the impact category, taking into account the chosen category indicator and identified category endpoint(s), and (4) identification of the characterization model and the characterization factors.						
45	Life cycle impact assessment	ISO 14044:2006, section 4.4	The impact categories, category indicators and characterization models should ideally be internationally accepted, i.e., based on an international agreement or approved by a competent international body.	Recommendation		OK	We recommend that you include a source or a link to where the reader can learn more about the applied LCIA methods.	This has been added in the report under section 3.2.1	OK
46	Life cycle impact assessment	ISO 14044:2006, section 4.4	It is recommended that the impact categories represent the aggregated impacts of inputs and outputs of the product	Recommendation	Requirement not applicable	Not applicable			

			system on the category endpoint(s) through the category indicators.						
47	Life cycle impact assessment	ISO 14044:2006, section 4.4	It is recommended that value-choices and assumptions made during the selection of impact categories, category indicators and characterization models is minimized.	Recommendation	Requirement met	OK			
48	Life cycle impact assessment	ISO 14044:2006, section 4.4	It is recommended that the impact categories, category indicators and characterization models avoid double counting unless required by the goal and scope definition, for example when the study includes both human health and carcinogenicity.	Recommendation	Requirement met	OK			

49	Life cycle impact assessment	ISO 14044:2006, section 4.4	It is recommended that the characterization model for each category indicator is scientifically and technically valid, and based upon a distinct identifiable environmental mechanism and reproducible empirical observation.	Recommendation	Requirement met	OK			
50	Life cycle impact assessment	ISO 14044:2006, section 4.4	It is recommended that the extent to which the characterization model and the characterization factors are scientifically and technically valid is identified.	Recommendation	Requirement met	OK			
51	Life cycle impact assessment	ISO 14044:2006, section 4.4	It is recommended that the category indicators are environmentally relevant.	Recommendation	Requirement met	OK			
52	Life cycle impact assessment	ISO 14044:2006, section 4.4	Depending on the environmental mechanism and the goal and scope, spatial and temporal differentiation of	Recommendation		OK			

			the characterization model relating the LCI results to the category indicator should be considered. The fate and transport of the substances should be part of the characterization model.						
53	Life cycle impact assessment	ISO 14044:2006, section 4.4	The environmental relevance of the category indicator or characterization model should be clearly stated in terms of the ability of the category indicator to reflect the consequences of the LCI results on the category endpoint(s), at least qualitatively.	Recommendation	Requirement met	OK			
54	Life cycle impact assessment	ISO 14044:2006, section 4.4	The environmental relevance of the category indicator or characterization model should be clearly stated in	Recommendation	Requirement met	OK			

			terms of the addition of environmental data or information to the characterization model with respect to the category endpoint(s), including (1) the condition of the category endpoint(s), (2) the relative magnitude of the assessed change in the category endpoints, (3) the spatial aspects, such as area and scale, (4) the temporal aspects, such as duration, residence time, persistence, timing, etc., (5) the reversibility of the environmental mechanism, and (6) the uncertainty of the linkages between the category indicators and the category endpoints.						

55	Life cycle impact assessment	ISO 14044:2006, section 4.4	Assignment of LCI results to impact categories should consider, unless otherwise required by the goal and scope, the assignment of LCI results that are exclusive to one impact category.	Recommendation	Requirement met	OK			
56	Life cycle impact assessment	ISO 14044:2006, section 4.4	Assignment of LCI results to impact categories should consider, unless otherwise required by the goal and scope, the identification of LCI results that relate to more than one impact category, including (1) distinction between parallel mechanisms, e.g. SO_2 is apportioned between the impact categories of human health and acidification and (2) assignment to serial mechanisms, e.g. NO_x can be classified to contribute to both ground-level	Recommendation	Requirement met	OK			

			ozone formation and acidification.						
57	Life cycle impact assessment	ISO 14044:2006, section 4.4	The method of calculating indicator results shall be identified and documented, including the value-choices and assumptions used.	Requirement	Requirement met	OK			
58	Life cycle impact assessment	ISO 14044:2006, section 4.4	If LCI results are unavailable or of insufficient data quality for the LCIA to achieve the goal and scope of the study, either an iterative data collection or an adjustment of the goal and scope are required.	Requirement	Requirement met	OK			
59	Life cycle impact assessment	ISO 14044:2006, section 4.4	The application and use of normalization, grouping and weighting methods shall be consistent with the goal and scope of the LCA and it shall be fully transparent. All methods and calculations used shall be documented to	Requirement	Requirement met	OK			

			provide transparency.						
60	Life cycle impact assessment	ISO 14044:2006, section 4.4	When applying normalisation, the selection of the reference system should consider the consistency of the spatial and temporal scales of the environmental mechanism and the reference value.	Recommendation	Requirement not applicable	Not applicable since normalization has not been applied			
61	Life cycle impact assessment	ISO 14044:2006, section 4.4	When applying weighting, it is recommended to use several different weighting factors and weighting methods, and to conduct sensitivity analysis to assess the consequences on the LCIA results of different value-choices and weighting methods.	Recommendation	Requirement not applicable	Not applicable since weighting has not been applied			
62	Life cycle impact assessment	ISO 14044:2006, section 4.4	When applying weighting, data and indicator results or normalized indicator results reached prior to	Recommendation	Requirement not applicable	Not applicable			

			weighting should be made available together with the weighting results.						
63	Life cycle interpretatio n	ISO 14044:200 6, section 4.5	The results of the LCI or LCIA phases shall be interpreted according to the goal and scope of the study, and the interpretation shall include an assessment and a sensitivity check of the significant inputs, outputs and methodological choices in order to understand the uncertainty of the results.	Requirement		Please include a sensitivity check of the significant inputs, outputs and methodological choices in order to understand the uncertainty of the results		Sensitivity check on contributing processes and phases has been conducted. Sensitivity check on the methodology choices has been made.	OK
64	Life cycle interpretatio n	ISO 14044:200 6, section 4.5	The interpretation shall consider, in relation to the goal of the study, the appropriateness of the definitions of the system functions, the functional unit and system boundary.	Requirement		Please add a few lines discussing the appropriateness of the defined system function, functional unit and system boundary under life cycle interpretation.		A section 6.1.2 has been added, discussing the appropriateness of the system, functional unit and system boundaries.	OK

65	Life cycle interpretatio n	ISO 14044:200 6, section 4.5	The interpretation shall consider, in relation to the goal of the study, the limitations identified by the data quality assessment and the sensitivity analysis.	Requirement		Please comment on how the identified limitations from the quality assessment and the sensitivity analysis affect the interpretation of the results.		A contribution analysis has been performed and investigation of the limitations and data quality has been added	OK
66	Life cycle interpretatio n	ISO 14044:200 6, section 4.5	When interpreting LCI results, and whenever feasible, it is recommended that characterization of uncertainty in results by ranges and/or probability distributions is performed to better explain and support the LCI conclusions.	Recommendatio n	Requirement not applicable	Not applicable			
67	Life cycle interpretatio n	ISO 14044:200 6, section 4.5	The life cycle interpretation phase of an LCA or an LCI study should identify any significant issues based on the results of the LCI and LCIA phases of LCA. Such issues include inventory data, impact	Recommendatio n	Requirement not applicable	Not applicable			

			categories, and contributions from life cycle stages to LCI or LCIA results.						
68	Life cycle interpretation	ISO 14044:2006, section 4.5	The life cycle interpretation phase of an LCA or an LCI study should perform an evaluation of the results based on completeness, sensitivity and consistency checks as well as uncertainty and data quality analysis.	Recommendation	Requirement not applicable	Not applicable			
69	Life cycle interpretation	ISO 14044:2006, section 4.5	The sensitivity check shall include the results of the sensitivity analysis and uncertainty analysis, if performed in the preceding phases (LCI, LCIA).	Requirement		Please include a sensitivity check		Sensitivity check with results from sensitivity analysis is added.	OK
70	Life cycle interpretation	ISO 14044:2006, section 4.5	If relevant to the LCA or LCI study, the consistency check should address whether (1) differences in data quality along a product system life cycle and between different product	Recommendation	Requirement met	OK			

			systems consistent with the goal and scope of the study, (2) regional and/or temporal differences have been consistently applied, (3) allocation rules and system boundary have been consistently applied to all product systems, and (4) the elements of impact assessment have been consistently applied.						
71	Life cycle interpretatio n	ISO 14044:200 6, section 4.5	The results of the evaluation should be presented in a manner that gives the commissioner or any other interested party a clear and understandable view of the outcome of the study.	Recommendatio n	Requirement met	OK	Note that section 5.1.1 states that fabric knitting with 0.471 is the third largest contribution to MTO - but transport to distribution is 0.476, thus, a bit higher. Moreover, we recommend to explain the unit "kg 1.4 DCB" since it - for most - is an unknown unit.	Has been checked and explanation of 1,4 kg DCB unit has been added in section 5.1	OK

72	Life cycle interpretatio n	ISO 14044:200 6, section 4.5	The life cycle interpretation phase of an LCA or an LCI study should include conclusions, limitations, and recommendation s. Whenever appropriate to the goal and scope of the study, specific recommendation s to decision-makers should be explained. Recommendation s should relate to the intended application.	Recommendatio n		OK			
73	Life cycle interpretatio n	ISO 14044:200 6, section 4.5	Recommendation s shall be based on the final conclusions of the study and shall reflect a logical and reasonable consequence of the conclusions.	Requirement		Include a conclusion with recommendatio ns at the end of the report		A section 6.6 includes a conclusion, and a section 6.7 includes recommendatio ns	OK
74	Life cycle interpretatio n	ISO 14040:200 6, section 5.5	The interpretation should reflect the fact that the LCIA results are based on a relative approach, that it indicates potential environmental	Recommendatio n		We recommend that the report describes what an LCA can and can not be used for, e.g., that the method is used to indicate potential		In the beginning of the interpretation In section 6, a description of what a LCA can and cannot has been added	OK

			effects and that it does not predict actual impacts on category endpoints, the exceedance of thresholds or safety margins or risks.			environmental effects.			
75	Reporting	ISO 14044:2006, section 5	The type and format of the report shall be defined in the scope phase of the study.	Requirement	Requirement met	OK			
76	Reporting	ISO 14044:2006, section 5	The results and conclusions of the LCA shall be completely and accurately reported without bias to the intended audience.	Requirement		Include a conclusion in the report		A conclusion in section 6.6 has been added.	OK
77	Reporting	ISO 14044:2006, section 5	The results, data, methods, assumptions, and limitations shall be transparent and presented in sufficient detail to allow the reader to comprehend the complexities and trade-offs inherent in the LCA.	Requirement		OK when previous comments have been implemented			OK
78	Reporting	ISO 14044:200	The report shall allow the results	Requirement	Requirement met	OK			

		6, section 5	and interpretation to be used in a manner consistent with the goals of the study.						
79	Reporting	ISO 14044:2006, section 5	When results of the LCA are to be communicated to any third party, i.e., interested party other than the commissioner or the practitioner of the study, regardless of the form of communication, a third-party report shall be prepared.	Requirement	Requirement met	OK			
80	Reporting	ISO 14044:2006, section 5	The third party report constitutes a reference document, and shall be made available to any third party to whom the communication is made. The third-party report shall cover the aspects described in section 5.2 of ISO 14044:2006.	Requirement	Requirement met	Transition must ensure this		The third-party report has been made based on the LCA report	OK
81	Reporting	ISO 14040:200	The third party report shall	Requirement	Requirement met	2.-0 LCA consultants will		The third-party report has been	OK

		6, section 5.2	describe the date of the report.			make sure this is done in the third party report.		made based on the LCA report.	
82	Reporting	ISO 14040:2006, section 5.2	The third party report shall describe the LCA commissioner and the practitioner of LCA (internal or external).	Requirement		2.-0 LCA consultants will make sure this is done in the third party report.		The third-party report has been made based on the LCA report.	OK
83	Reporting	ISO 14044:2006, section 5	The third party report shall include a statement that the study has been conducted according to the requirements of ISO 14044:2006 and ISO 14040:2006.	Requirement		2.-0 LCA consultants will make sure this is done in the third party report.		The third-party report has been made based on the LCA report.	OK
84	Public comparative assertions	ISO 14044:2006, section 5	The third party report shall include a statement regarding whether the study intends to support comparative assertions intended to be disclosed to the public.	Requirement		2.-0 LCA consultants will make sure this is done in the third party report.		The third-party report has been made based on the LCA report.	OK
85	Reporting	ISO 14040:200	The third party report shall describe the assumptions	Requirement		2.-0 LCA consultants will make sure this is done in the		The third-party report has been	OK

		6, section 5.2	about electricity production.			third party report.		made based on the LCA report.	
86	Reporting	ISO 14044:2006, section 5	If any normalization, grouping or weighting is performed, the third party report shall include the data and indicator results reached prior to any normalization, grouping or weighting shall be made available together with the normalized, grouped or weighted results.	Requirement	Requirement not applicable	Not applicable			
87	Reporting	ISO 14044:2006, section 5	If grouping of the impact categories is performed, the third party report shall include a statement and justification of any grouping of the impact categories.	Requirement	Requirement not applicable	Not applicable			
88	Reporting	ISO 14044:2006, section 5	The third party report shall include a statement that the LCIA results are relative expressions and do not predict impacts on	Requirement	Requirement not applicable	Not applicable			

			category endpoints, the exceeding of thresholds, safety margins or risks.						
89	Critical review	ISO 14044:2006, section 6	The scope and type of critical review desired shall be defined in the scope phase of an LCA, and the decision on the type of critical review shall be recorded.	Requirement	Requirement met	OK			
90	Critical review	ISO 14044:2006, section 6	The review statement and review panel report, as well as comments of the expert and any responses to recommendations made by the reviewer or by the panel, shall be included in the LCA report.	Requirement		Transition must ensure this		Will do when review is done	OK
91	Public comparative assertions	ISO 14044:2006, section 4.2	Where the study is intended to be used in comparative assertions intended to be disclosed to the public, the final sensitivity analysis of the inputs and outputs data shall include the	Requirement	Requirement not applicable	Not applicable			

			mass, energy and environmental significance criteria so that all inputs that cumulatively contribute more than a defined amount (e.g., percentage) to the total are included in the study.						
92	Public comparative assertions	ISO 14044:2006, section 4.4	An LCIA that is intended to be used in comparative assertions intended to be disclosed to the public, shall employ a sufficiently comprehensive set of category indicators. The comparison shall be conducted category indicator by category indicator.	Requirement	Requirement not applicable	Not applicable			
93	Public comparative assertions	ISO 14044:2006, section 4.4	An LCIA shall not provide the sole basis of comparative assertion intended to be disclosed to the public of overall environmental	Requirement	Requirement not applicable	Not applicable			

			superiority or equivalence, as additional information will be necessary to overcome some of the inherent limitations in LCIA. Value-choices, exclusion of spatial and temporal, threshold and dose-response information, relative approach, and the variation in precision among impact categories are examples of such limitations.						
94	Public comparative assertions	ISO 14044:2006, section 4.4	Category indicators intended to be used in comparative assertions intended to be disclosed to the public shall as a minimum be (1) scientifically and technically valid, i.e., using a distinct identifiable environmental mechanism and/or reproducible empirical	Requirement	Requirement not applicable	Not applicable			

			observation; and (2) environmentally relevant, i.e., have sufficiently clear links to the category endpoint(s) including, but not limited to, spatial and temporal characteristics.						
95	Public comparative assertions	ISO 14044:2006, section 4.4	Category indicators intended to be used in comparative assertions intended to be disclosed to the public should be internationally accepted.	Recommendation	Requirement not applicable	Not applicable			
96	Public comparative assertions	ISO 14044:2006, section 4.4	Weighting shall not be used in LCA studies intended to be used in comparative assertions intended to be disclosed to the public.	Requirement	Requirement not applicable	Not applicable			
97	Public comparative assertions	ISO 14044:2006, section 4.4	An analysis of results for sensitivity and uncertainty shall be conducted for studies intended to be used in comparative	Requirement	Requirement not applicable	Not applicable			

			assertions intended to be disclosed to the public.						
98	Public comparative assertions	ISO 14044:2006, section 4.5	When an LCA is intended to be used in comparative assertions intended to be disclosed to the public, the evaluation element shall include interpretative statements based on detailed sensitivity analyses.	Requirement	Requirement not applicable	Not applicable			
99	Public comparative assertions	ISO 14044:2006, section 5.3	The third party report shall describe, for LCA studies supporting comparative assertion intended to be disclosed to the public, an analysis of material and energy flows to justify their inclusion or exclusion.	Requirement	Requirement not applicable	Not applicable			
100	Public comparative assertions	ISO 14044:2006, section 5.3	The third party report shall describe, for LCA studies supporting	Requirement	Requirement not applicable	Not applicable			

			comparative assertion intended to be disclosed to the public, an assessment of the precision, completeness and representativeness of data used.						
101	Public comparative assertions	ISO 14044:2006, section 5.3	The third party report shall describe, for LCA studies supporting comparative assertion intended to be disclosed to the public, a description of the equivalence of the systems being compared.	Requirement	Requirement not applicable	Not applicable			
102	Public comparative assertions	ISO 14044:2006, section 5.3	The third party report shall describe, for LCA studies supporting comparative assertion intended to be disclosed to the public, a description of the critical review process.	Requirement	Requirement not applicable	Not applicable			

103	Public comparative assertions	ISO 14044:2006, section 5.3	The third party report shall describe, for LCA studies supporting comparative assertion intended to be disclosed to the public, an evaluation of the completeness of the LCIA.	Requirement	Requirement not applicable	Not applicable			
104	Public comparative assertions	ISO 14044:2006, section 5.3	The third party report shall include, for LCA studies supporting comparative assertion intended to be disclosed to the public, a statement as to whether or not international acceptance exists for the selected category indicators and a justification for their use.	Requirement	Requirement not applicable	Not applicable			
105	Public comparative assertions	ISO 14044:2006, section 5.3	The third party report shall include, for LCA studies supporting comparative assertion intended to be disclosed to the	Requirement	Requirement not applicable	Not applicable			

			public, an explanation for the scientific and technical validity and environmental relevance of the category indicators used in the study.						
106	Public comparative assertions	ISO 14044:2006, section 5.3	The third party report shall describe, for LCA studies supporting comparative assertion intended to be disclosed to the public, the results of the uncertainty and sensitivity analyses.	Requirement	Requirement not applicable	Not applicable			
107	Public comparative assertions	ISO 14044:2006, section 5.3	The third party report shall describe, for LCA studies supporting comparative assertion intended to be disclosed to the public, an evaluation of the significance of the differences found.	Requirement	Requirement not applicable	Not applicable			

108	Public comparative assertions	ISO 14044:2006, section 6	In order to decrease the likelihood of misunderstandings or negative effects on external interested parties, a panel of interested parties shall conduct critical reviews on LCA studies where the results are intended to be used to support a comparative assertion intended to be disclosed to the public.	Requirement	Requirement not applicable	Not applicable			
109	Free text for reviewer	ISO 14044:2020	Any other topics, requirements, and recommendations by the reviewer which are not explicitly mentioned by ISO standards.	Not applicable					