Master's Thesis Internship – M.Sc. Sustainable Business and Innovation

Linking the Planetary Boundaries to the Life Cycle Environmental Impacts of Cotton T-shirts in the Netherlands

The implications and limitations of the application in term of impact-reduction strategy for clothing companies

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A master thesis (23718 words)

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Abstract

For the past few years, researchers has been attempting to apply the Planetary boundaries (PBs) to the Life Cycle Assessment (LCA) framework, as they hope the connection would allow us to understand the impacts and limits of human activities towards the Earth system better, and to ultimately maintain the Holocene-like ecological state. One of the recent applications is the development of impact-reduction target for the life cycle environmental impacts of a product in relation to the PBs, of the which the first procedure for the development was introduced by Sandin et al. (2015) – which in this thesis the procedure was called "Sandin's procedure". Accordingly, the researchers applied the procedure to a case study of Swedish clothing consumption and use the result as guidance for the government to prioritize interventions for impact reduction. However, the results of their study were not beneficial for clothing company to use as the scope of their environmental responsibility covers the entire value chain, not just the product consumption phase. Thus, the implications for the business sector has yet to be explored.

In this thesis, Sandin's procedure was used to develop impact-reduction targets for the LCA of clothing products (from cradle-to-grave): the chosen case-study was cotton T-shirt used in the Netherlands. The main objective was to explore the implications in term of impact-reduction strategy for clothing companies. The research entailed both the LCA of the products and the development of the targets. By combining the result of both studies, the final result was used to interpret the implications, which mostly involved with the prioritization of impact category and phase of impact-reduction intervention, advantageous location for business operation (where there are low environmental impacts and reduction targets). However, despite the implications, the result were concluded to be yet practical for implementation in term of the targets and even the concept of Sandin's procedure itself. For the targets, many of them were extremely high, and it would require large-scale technological innovation and cross-industrial cooperation to achieve – thus, not logical to focus on a business sector scale. The scientific limitations of Sandin's procedure also jeopardize the accuracy of the impact-reduction targets as well. These limitations are, for examples, the incompatibility between the PB and LCA, and the lack of concrete allocation method both for the specific market segment and geographical scope. This leads to further research recommendations for improving the concept.

Executive summary

For the past few years, scientists and researchers have been attempting to create link between the Planetary Boundary (PB) and the Life Cycle Assessment (LCA) framework together (Bjørn & Hauschild, 2015; Fang, Heijungs, & Snoo, 2015; Tuomisto et al., 2012). They believe that by bridging the gap between the environmental impacts of a product or human activity (LCA) and the ecological states of the Earth system (PB), we would be able to understand the impact of our actions towards the Earth system, and able to ultimately maintain the Holocene-like state.

Accordingly, one of the recent studies is to use the PB-framework to develop the quantitative targets for impact reduction at a product scale, as the concept promises potential usefulness to sustainability management of the public and private sector, and the procedure for the development was firstly introduced by Sandin and colleague in 2015 (Sandin, Peters, & Svanström, 2015) – in this thesis the procedure would be called "Sandin's procedure". In their study, the procedure was applied to a case-study of Swedish clothing consumption, and the result was suggested as guidance for Swedish government or policymakers to evaluate and prioritize intervention for impact reduction (ibid.). However, although the result of their study might prove significance to the public sector, it was not particularly useful for the business sector in the clothing industry, as the processes related to the business operation like raw material production and product manufacturing were not covered. Furthermore, if a company would like to commit in sustainability management fully, it needs to consider reducing its environmental impact throughout the value chain of their business – including raw material production, product manufacturing, distribution, consumption and disposal (D'heur, 2015). Hence, the application of Sandin's procedure (throughout the lifecycle of a clothing product) from the perspective of clothing company has yet to be explored.

In this thesis, Sandin's procedure was used to develop the impact-reduction target for clothing products. The reduction targets were then applied to an LCA case-study of cotton T-shirts (cradle to grave). The main objective was to explore possible applications of the result for clothing companies in term of sustainability management. Hence, the research question of this thesis was structured as follows:

"*By applying the impact-reduction targets from Sandin's procedure to the LCIA of cotton clothes in the Netherlands, what are the implications for impact reduction strategy along the value chain of clothing companies?*"

The secondary objective of this study was to discuss the practicality of the implications and the existing limitations in linking Sandin's procedure to LCIA of a product, which would be described after the main research question above had been answered.

Regarding the case-study, two cotton T-shirts in the Netherlands were studied; one with cotton fiber production from the United States, and another from China. The two countries cover almost 40% of the world cotton production (Beton, Dias, Farrant, Gibon, & Le Guern, 2014). The reason for studying both products was to cope with the inability of locating the exact fiber source, since this research was not collaborated with any clothing firm; the actual context was therefore not realized. Accordingly, both products were assumed to be manufactured in China and were distributed to the Netherlands, where they were consumed for a period of time before being disposed away in the end. The rationale of choosing China as the manufacturing countries was because the country is the largest clothing exporter in the world (World Trade

Organization (WTO), 2017), while the Netherlands was chosen because of its high amount clothing consumption (Euractiv, 2016; Maldini et al., 2017).

Correspondingly, two separated studies were conducted on the case-study. The first one was the LCA of the cotton T-shirt, and the second one was the development of impact-reduction targets of the products using Sandin's procedure. In the LCA study, the environmental impact of the product throughout the lifecycle was assessed. The study began with LCA literature review of cotton products in order to understand the context, and to identify significant hotspot activities. After that, the LCA of the cotton T-shirt was conducted. The data for the products' life-cycle inventory was collected from secondary sources, comprising of LCA literature, Ecoinvent database, and publicly online information. Three impact categories were chosen for the assessment – these are climate change, freshwater eutrophication and freshwater consumption – because they were identified as significant in cotton products based on the literature review. The impact assessment was conducted using ReCiPe model in Simapro software.

As for the impact-reduction targets development from PB-framework, this thesis followed the method in Sandin's procedure (Sandin et al., 2015), which can be mathematically described as followed:

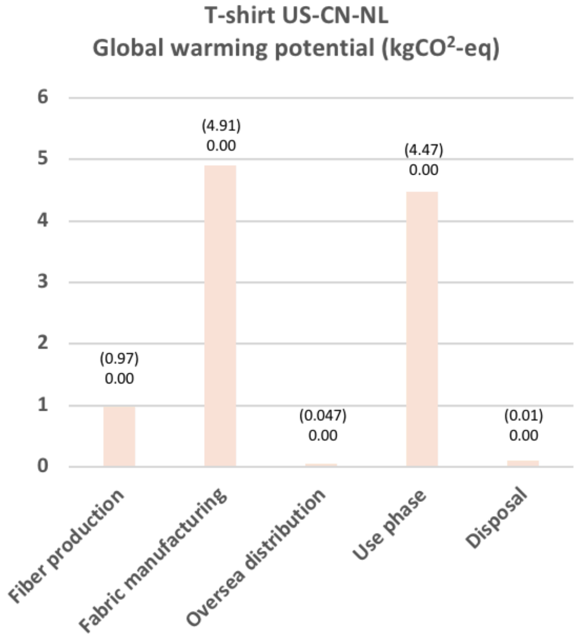
$$\mathbf{RT_{X,Y,Z} = 100\text{-}(100\text{-}RT_{X}) * A_{market,\,Y} * A_{region,\,Z}}$$

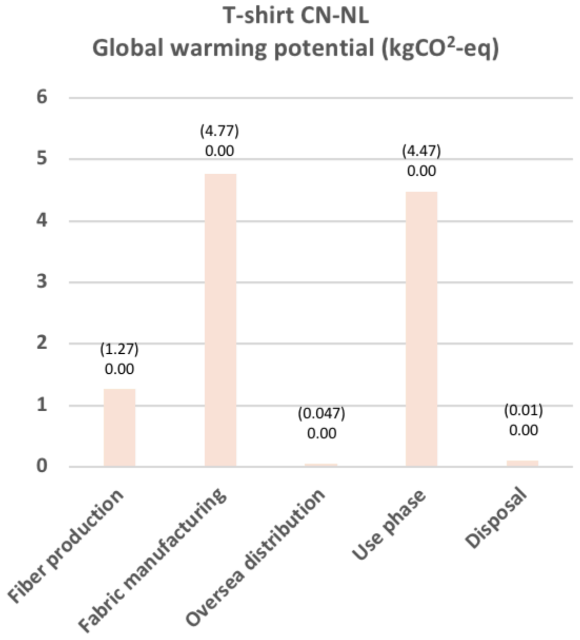
The procedure began with the development of the global impact-reduction target for each PB [$\mathbf{RT_{X}}$], which was already developed by Sandin et al., in order to identify the globally allowed impact $\mathbf{[100\text{-}RT_{X}]}$. Then, each globally allowed impact was allocated to the specific market segment and the geographical scope in which the product or the process within the product's lifecycle belonged to [$\mathbf{(100\text{-}RT_{X}) * A_{market,\,Y} * A_{region,\,Z}}$]. Finally, the allocated, allowed impact was then converted into the impact-reduction target of the product [$\mathbf{100\text{-}(100\text{-}RT_{X}) * A_{market,\,Y} * A_{region,\,Z}}$] or [$\mathbf{RT_{X,Y,Z}}$].

By combining the LCIA result of the two cotton T-shirt and the chosen impact-reduction targets for the products, the research question was answered. **Figure 1** (next page) shows the comparison between the original environmental impact of the two cotton T-shirts in each lifecycle phase and the post-reduction impact after being reduced in according to the impact-reduction targets. The gap between the two quantities represents how much the impacts need to be reduced by that time. The result of the cotton T-shirt of which the fibers were produced in the United States is labeled as "T-shirt US-CN-NL". Correspondingly, the result of the cotton T-shirt of which the fibers were produced in China is labeled as "T-shirt CN-NL".

The result suggested a drastic reduction of the overall impacts throughout the life-cycle of both products, especially climate change (refer to global warming potential), as all the current impact had to be reduced down to zero *in term of net impact*, regardless of geographical scope and market segment. This means that after balancing all the release and offset of greenhouse gases (GHG), the net GHG emission in each phase of the products' lifecycle must be equal to zero. Similarly, the impact-reduction targets for freshwater eutrophication were very high throughout the life-cycle of both cotton T-shirts (70-90%). As for freshwater consumption, there was a gap difference between the impact-reduction targets of the three countries, whereas China and the Netherlands had an exceptionally low targets (22-29%) in comparison to the United States (62%).

Accordingly, several implications can be made from the result for clothing companies in term of environmental impact reduction strategy throughout the life-cycle of a cotton T-shirt. First of all, the result indicated an advantageous position for business development in China, where the impact-reduction targets were lower than in the United States. Also, clothing companies that currently sell T-shirt US-CN-NL should prioritize in reducing the water consumption in the fiber production rather than the use phase, despite lower consumption, as the impact-reduction target of the process was twice higher than the use phase. Secondly, the result suggested prioritization in impact reduction of climate change and freshwater eutrophication in the fabric manufacturing phase and use phase. In climate change, since it was realistically impossible to achieve zero net emission through GHG emission mitigation only, the option of GHG offsetting programs and carbon credit should be considered as part of the impact reduction strategy. In freshwater eutrophication, unlike climate change, the targets were not expressed in net impact; the impact therefore could not be offset. Thus, it is most challenging to mitigate freshwater eutrophication as phosphorus related compounds were necessarily used in many phases of the products – either as direct and indirect inputs.


T-shirt US-CN-NL
Global warming potential (kgCO^2-eq)


T-shirt CN-NL
Global warming potential (kgCO^2-eq)

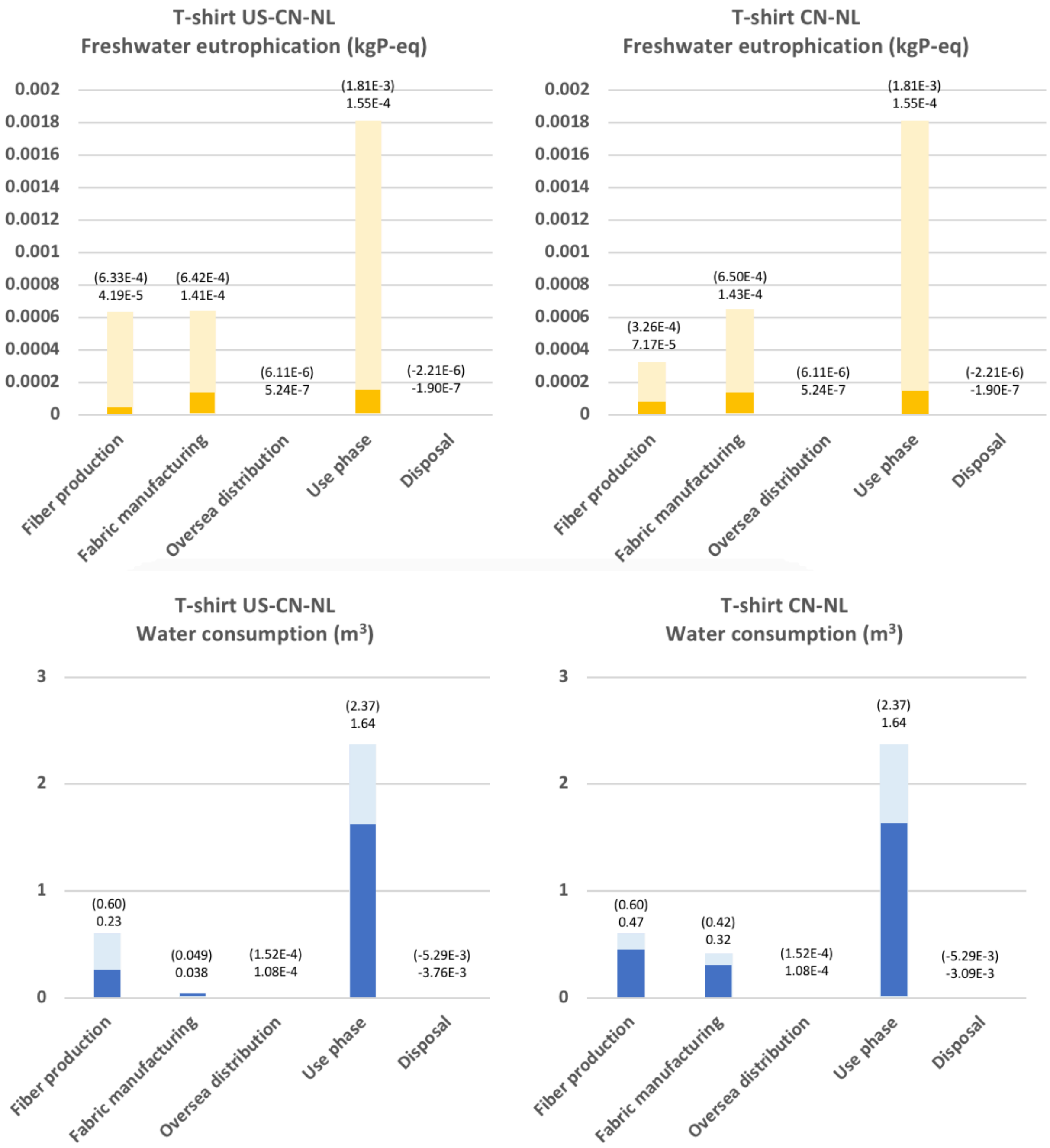


Figure 1: The comparison between the original environmental impact (darker color) of the two cotton T-shirts in each lifecycle phase and the post-reduction impact (lighter color) after being reduced in according to the impact-reduction targets. The functional unit of both product is a 100% white, short-sleeved cotton T-shirt that is worn regularly for 1 year. The environmental impacts include in the assessment are climate change, freshwater eutrophication, freshwater consumption. The numbers with brackets represents the original quantitative impact, while the number without brackets represent the post-reduction impacts.

However, despite the implications, the result was not yet suitable to be used in real practice by companies, especially in setting the quantitative goal in impact reduction strategy. This was because the targets were considered to be impractical both in term of the target number and in term of science.

In term of target number, the developed impact-reduction targets in this case-study was considered to be unrealistic for clothing companies to achieve. From the analysis of 13 current-best technological interventions for impact reduction in the European clothing sector from cradle to grave, conducted by Beton et al. (2014), the existing technological interventions are still incapable of reducing the impact that high. The study concluded that the maximum rate of impact reduction for climate change, freshwater eutrophication, and water consumption are 22%, 28%, and 35% respectively. Also, it would require more than just a clothing sector alone, but rather a cross-industrial impact reduction to massively reduce the targeted amount of impact. Hence, it might be more logical to apply Sandin's procedure in the country scale rather than one single business sector.

In term of scientific impracticality, there were major limitations in the application of Sandin's procedure to the LCA of products. To begin with, there was an issue of incompatibility between PB and LCA framework, where not all PBs could be directly compared to the impact category in LCA due to the misalignment between the PB's control variables and LCA's impact indicators. Though, there has been a study which proposed a new set of characterization factors (CFs) specifically for the PBs (Ryberg, Owsianiak, Richardson, & Hauschild, 2018a), as an attempt to solve the issue. The set of CFs is still, however, a proof-of-concept and have yet to entirely solve all the misalignment issues mentioned in this study. Additionally, the current exclusion of many other LCA impact categories by the PBs also raised a future research question whether is it necessary to identify the absolute boundaries for those impacts or not (if we were to create a link between the planetary boundaries and the impact of a product/activity entirely). Another limitation is the current absence of regionalized PBs which jeopardize the credibility of the impact-reduction targets, as the PB for many Earth system processes should have different boundaries depending on the regional context. Last but not least, several limitations in the allocation method of Sandin's procedure were identified as well. For example, there was a lack of concrete set of indices for determining the allocation factor of products in different market segment ($\mathbf{A}_{\mathbf{market,\,Y}}$), as well as, a lack of methodology to deal with the situation when a process has more than one impact-reduction targets. Also, the allocation factor of specific geographical scope was sensitive to the choice of variable used to calculate the allocation factor, and thus it is important to validate and rationalize the choice carefully.

In conclusion, by applying the impact-reduction targets from Sandin's procedure to the LCIA of clothing products, the result implies several trajectories toward impact-reduction strategy for clothing companies. However, due to the impracticality of the result and concept identified in this thesis, particularly the limitations in linking the PB and LCA-framework, and the limitations in the allocation method of Sandin's procedure, the application of the procedure to the LCIA remains to be a theoretical concept rather than a practical one, at least not until further improvements are made. Some of these improvements are described as further research recommendations below:

- Improving the compatibility between PB and LCA framework. Further testing and validation of the set of the characterization factors for the control variables of PBs introduced by Ryberg et al. (2018a) could be one of the research trajectories.
- Exploring whether there is a need to find an absolute boundary for the currently excluded LCA impact categories or not.
- Developing the framework for identifying the regional boundary in according to different geographical context.
- Designing a concrete set of indices for calculating the allocation factor for specific market segment.

Table of Contents

List of abbreviations

Abbreviations	Meaning
CF	Characterization factor
CN	China
EU	Europe
GLO	Global
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
NL	The Netherlands
PB	Planetary boundary
RER	Europe
RoW	Rest of the world
US	The United States

1. Introduction

In 1972, when a group of leading scientists from the Club of Rome published a report 'The Limit to Growth' (Meadows et al., 1972), introducing the future scenario as a result of human activities, the world began to realize about the degradation of the Earth's environment as well as mankind's future. Since then, scientists around the world have been studying about the consequences of all human activities that might negatively affect the planet and its limits.

Accordingly, one of the important tools for studying the environmental impact is called Life Cycle Assessment – shortly known as LCA. The tool is commonly used to assess the impact of a product/activity throughout its life-cycle (International Organization for Standardisation (ISO), 2006). Initially, it was used with scattered methodologies and measures, but at the end of the 20th century, an international standard was developed by ISO (ibid.). Today, LCA has become one of the common tools for scientists and businesses to assess the impact of various products.

However, despite the tremendous amount of LCA studies, the 'limits' of human activities are still hardly understood. In 2009, when Rockström and his colleagues published a paper introducing the concept of Planetary Boundary (PB) framework, outlining nine biophysical boundaries of the Earth system that must be respected in order to prevent the uncertainty of causing non-linear environmental changes, which would result in functional collapses in the ecosystems (Rockström et al., 2009). Their finding helped identify the 'safe-operating spaces' of the planet, and consequently allowed scientists to recognize how far (close) are we to reach the point of no return. More importantly, the study also shades light towards the possibility of identifying the absolute limits of human activities.

As a result, many researchers have been attempting to link the PB to LCA framework over the past few years (e.g. Bjørn & Hauschild, 2015; Fang, Heijungs, & Snoo, 2015; Tuomisto et al, 2012). They believe that by bridging the gap between the environmental impact of a product or human activity (LCA) and the ecological states of the Earth system (PB), they would be able to understand the contribution of human activities and their limits towards the planet system better.

Accordingly, one of the most recent study is the development of impact-reduction targets of a product under the PB, which is a study that promises potential benefits to sustainability management (Sandin et al., 2015). By knowing how much impacts a product is allowed to create under the Earth's boundaries, companies can channel their investment to the most effective impact-reduction strategy along its supply chain. However, so far there has been only one study (at least in the published one) that looks into the topic, and that particular study was conducted by Sandin et al. (2015).

In their study, Sandin et al. proposed a procedure for "*using the PB framework to set quantitative targets for impact reduction at the product scale*" (Sandin et al., p.1685) – which from now would be called "Sandin's procedure" for the rest of this thesis. They used the procedure to identify the impact reduction targets for their case study – Swedish clothing consumption. The result was suggested as a guide for Swedish government or policy makers to evaluate and prioritize interventions for impact reduction (ibid.).

Despite the significance of the result, however, it was not particularly useful to the clothing companies (in term of sustainability management). For a company to fully commit to its corporate sustainability, it needs to consider reducing its environmental impact throughout the value chain of their business – in other words the entire lifecycle of the product, including fiber production, fabric manufacturing, product consumption and disposal (D'heur, 2015). However, in Sandin et al. (2015), Sandin's procedure was not apply to a lifecycle context, rather they only consider the consumption phase of the product into account. Therefore, if clothing companies would like to make use of Sandin's procedure, it would be more logical to apply the procedure throughout the lifecycle of the product (cradle to grave).

For this reason, in this thesis, Sandin's procedure is going to be used to set quantitative targets for impact reduction throughout the lifecycle of clothing products. The targets would then be applied to the life cycle environmental impacts of a product. The primary objective is to explore the implications of the result for impact reduction strategy along the value chain of clothing companies. The secondary objective is to discuss the practicality of the implications, as well as the limitations of applying Sandin's procedure to the life cycle of environmental impacts. The result of the study is expected to contribute further understanding of the use and limitations of Sandin's procedure, and to advocate future research agenda.

The case-study of this thesis would be products from clothing industry, particularly cotton products. The rationale for the selection is based on the fact that cotton is the most consumed non-synthetic fibers worldwide (despite the rise of synthetic fibers) (FAO/ICAC, 2013) (**Figure 2**). In the clothing industry, cotton fiber alone account for more than 30% of the world clothing fiber consumption (ibid.) (**Figure 3**). Additionally, the fiber shared an almost equal amount of consumption with synthetic fibers among the developed countries (ibid.) (**Figure 4**). Cotton fiber also has highly unsustainable production process in term of both the environmental pollutions (e.g. pesticides and chemical fertilizers) and resource depletion (e.g. water and land-use) (Cotton Incorporated, 2012). Additionally, India, China, and the United States are the major cotton-producing countries; their production size altogether covers about 70% of the world cotton production (**Figure 5**) (Statista, 2017)

Contrary to Sandin's case-study, which only focused on the consumption, the system-boundary in this case-study would cover the entire lifecycle of the products (cradle to grave). Correspondingly, two cotton clothes are chosen; one with fiber production source from the United States (US) and another from China. The reason for studying both products is because, due to the complexity of cotton supply-chain (Masson, Iosif, Mackerron, & Fernie, 2007), it is difficult to accurately identify where the fiber source of cotton cloth would come from. Therefore, cotton clothes with raw materials procured from two main producing countries – US and China – are chosen for the case-study. Together, they covered 40% of the global cotton production in 2016/17 (**Figure 5**) (Statista, 2017). In product manufacturing, both products are assumed to be manufactured in China, as the country is the world top's clothing exporter, holding more than 35% of the global share (World Trade Organization (WTO), 2017). As for the consuming country (including disposal), the Netherlands is chosen because it is among the top consuming countries in Europe (Euractiv, 2016); the continent has high rate of clothing consumption as well as the highest share of global clothing import (WTO, 2017). Base on the quantitative assessment by Hogeschool van Amsterdam and its associates (**Figure 6**), a Dutch person buys 46 clothing items, possesses 173 items in their wardrobe, and dispose of 40 items every year (Maldini et al., 2017) – thus, an excessive consumption behavior that worth further investigation. Moreover, China is one of the biggest exporting countries of clothing products in the Netherlands, where 20% of the products are imported from the country alone (World Integrated Trade Solution (WITS), 2015).

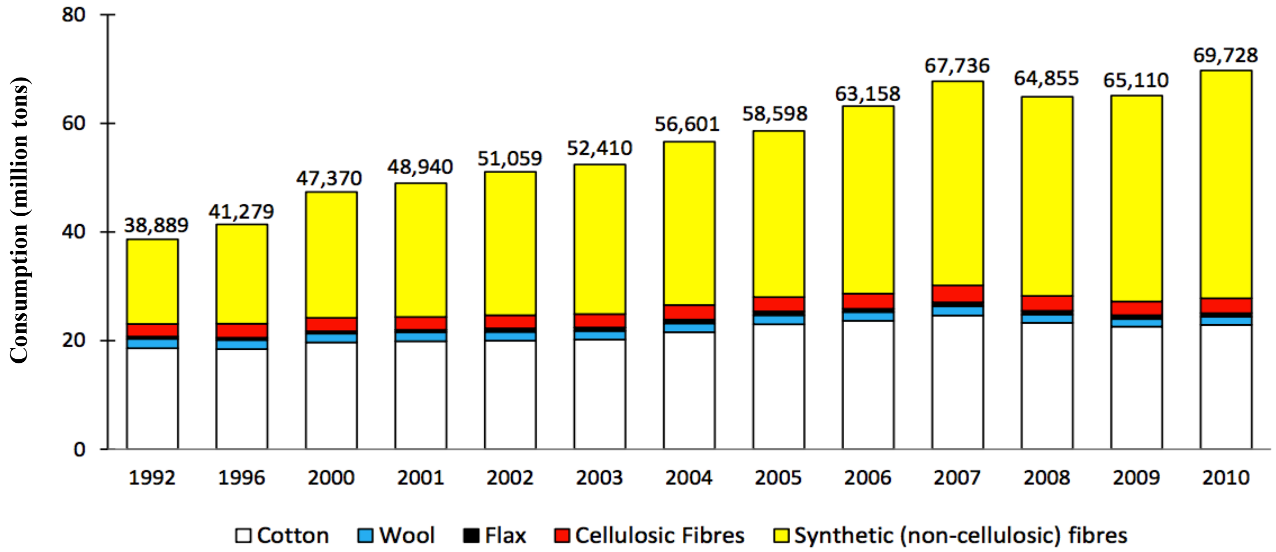


Figure 2: Evolution of world apparel fiber consumption in million tons (FAO/ICAC, 2013). Figure courtesy of FAO/ICAC.

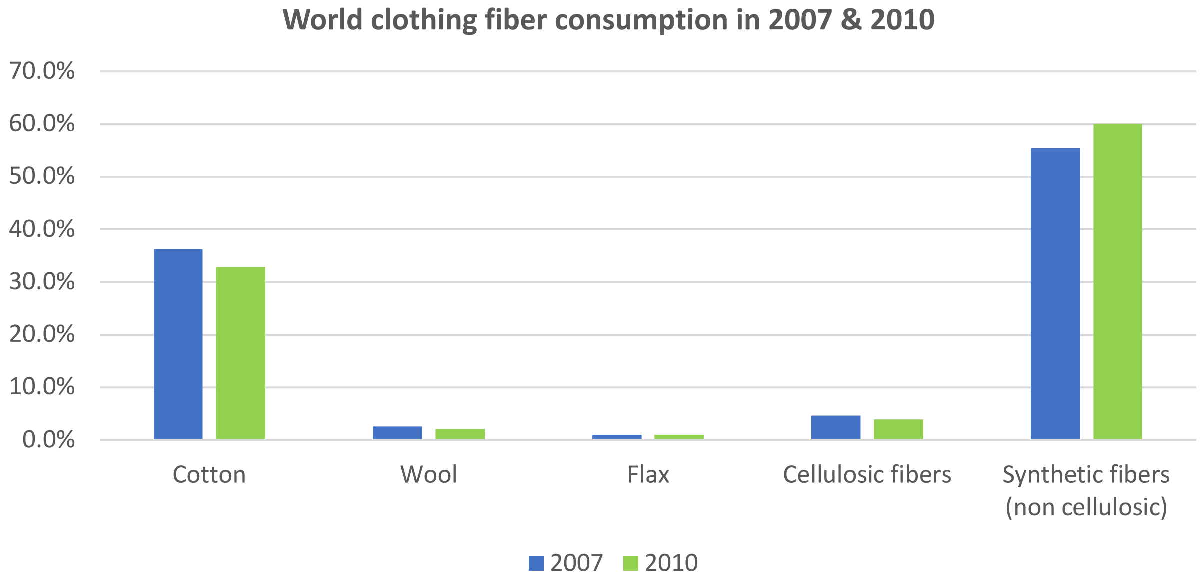


Figure 3: Composition of world clothing fiber consumption by fiber type, in percentage. (FAO/ICAC, 2013)

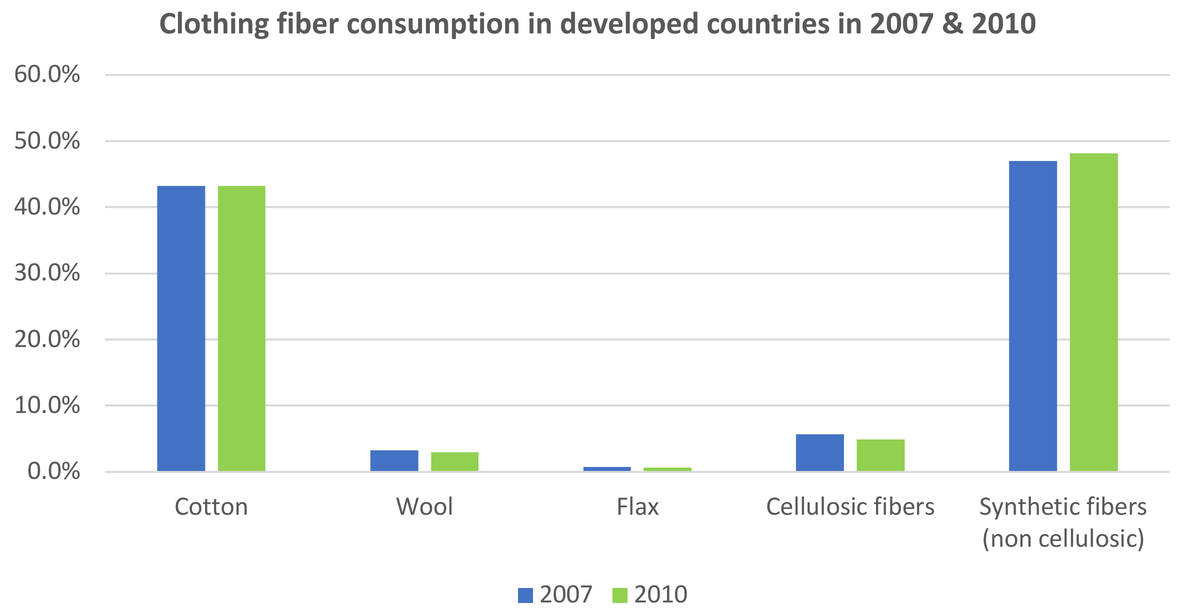


Figure 4: Composition of clothing fiber consumption in developed countries by fiber type, in percentage. (FAO/ICAC, 2013)

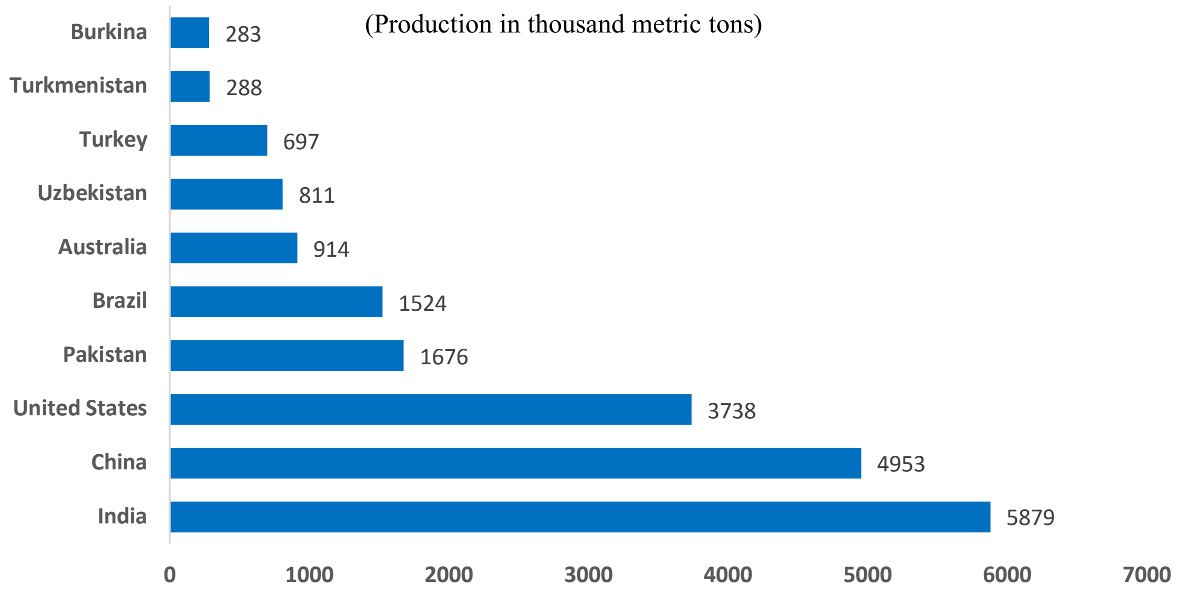


Figure 5: Leading cotton producing countries worldwide in 2016/2017 (thousand metric tons) (Statista, 2017)

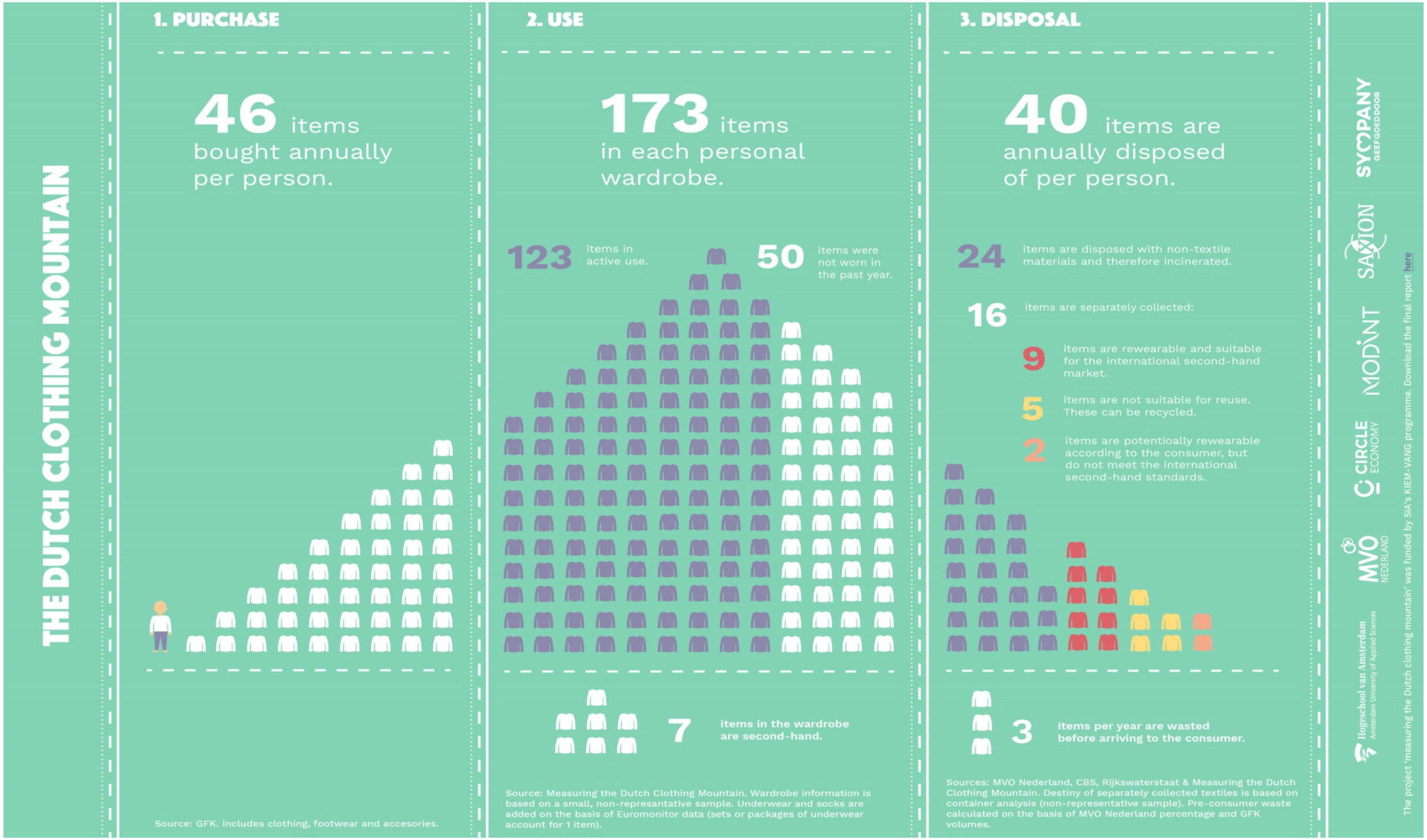


Figure 6: The average Dutch consumption behavior on clothing products in 2010-2017 (Maldini et al., 2017). Figure courtesy of Maldini et al. (2017)

Thus, the research question of this thesis is established in according to the primary objective, which is described as follow:

"*By applying the impact-reduction targets from Sandin's procedure to the LCIA of cotton clothes in the Netherlands, what are the implications for impact reduction strategy along the value chain of clothing companies?*"

To answer the research question, two separated studies are going to be conducted: 1) the lifecycle assessment of cotton clothes in the Netherlands, and 2) the development of impact reduction target (in %) of the products using Sandin's procedure. By combing the result of both studies, the research question could be answered.

As for the secondary objective of this study, which is to discuss the practicality of the implications and the limitations of applying Sandin's procedure to lifecycle impact assessment of a product, they would be discussed in the discussion chapter (Chapter 6) after the primary objective has been achieved.

The structure of this thesis is described as follow:

In Chapter 2, the theories of lifecycle impact assessment, the planetary boundary, and Sandin's procedure would be introduced, in order to build a proper understanding of the theoretical framework in this thesis.

In Chapter 3, the research methodology such as research process and data collection method are described.

In Chapter 4, the preliminary results of the study (i.e. literature review and lifecycle inventory analysis) used to produce the final result are shown.

In Chapter 5, the final results are shown and the interpretation of the result are described. Here, the research questions would also be answered.

In Chapter 6, the practicality and the limitations of the application and the study would be discussed, with further research recommendations.

Finally, the conclusion of the study is summarized in Chapter 7.

2. Theoretical framework

As already explained in Chapter 1, in this thesis, the impact reduction targets developed from the PB-framework, using Sandin's procedure, is going to be applied to the LCIA of cotton clothes, in order to fulfill the current disconnection between specific human activities and their impacts towards the planet (Bjørn & Hauschild, 2015; Sandin et al., 2015). The objective is to explore possible implications clothing companies to improve the environmental impacts along their value chain, and to identify the limitations of the application. To do this, two separate studies are going to be conducted: (1) the life-cycle assessment of cotton T-shirts in the Netherlands, and (2) the development of impact-reduction targets of the cotton T-shirt from the PB-framework using the procedure proposed by Sandin et al. (2015).

In this chapter, the theoretical concepts related to the study are going to be introduced in order to offer proper understanding related to the researches; these are (1) Life Cycle Assessment (LCA), (2) the Planetary Boundary (PB), and (3) Sandin's procedure for developing the quantitative targets for impact reduction at product scale (using the PB).

2.1 Life Cycle Assessment (LCA)

The most common method for scientists to assess the impact of a product or activity is known as 'Life Cycle Assessment (LCA)'. It is a tool used to assess the environmental/health impacts of a product throughout it life-cycle, and is recommended by the International Organization for Standardizations (ISO) (ISO, 2006). Its applicability has also been expanding outside the academic realm towards many industrial sector. Through LCA, practitioners can assess various environmental impacts, such as, global warming potential, water resource depletion, eutrophication, and human toxicity.

There are four main steps when conducting LCA; these are (1) Goal and scope definition, (2) Inventory analysis, (3) Impact assessment, and (4) Interpretation (ibid.).

Goal and scope definition: The first phase determines the context and structure of the LCA. It outlines the fundamental information needed for conducting the LCA, for examples, the specific product/process to be assessed (scope-boundary), the functional unit of the product, the type of data within the specified process and functional unit that should be included in the assessment.

Life Cycle Inventory (LCI): The process in the second phase involves the collection and modelling of data of all the materials and their flows within the scope boundary. The collected data would then be used to assess and interpret the impact of the product and its processes. Although this is the most laborious and resource-consuming phase, it also a crucial phase which would influence the impact assessment phase. Practitioners need to ensure that the data is accurate and comprehensive.

Life Cycle Impact Assessment (LCIA): Once the data of the elementary flow is collected, they are translated into indicators for various impact categories that reflect potential environmental and health impacts. This is done by multiplying and also aggregating the characterization factors of each impact category to the elementary flows.

Interpretation of results: In the last phase, the conclusion of the study is made by combining the finding from the inventory analysis and impact assessment in consistent with the defined goal and scope (ibid.). Additionally, the interpretation might involve the processes of reviewing and revising of the scope, and the nature or the quality of the data collected – for example, inventory completeness check and sensitivity analysis.

2.2 The Planetary Boundary (PB)

There have been several researches attempting to identify global 'limits' of environmental impacts (e.g. Arrow et al., 1996; Harris & Kennedy, 1999; Rees, 1992; Rockström et al., 2009). However, one of the famous studies that have been vastly discussed among the science society is the PB-framework introduced by Rockstorm et al. in 2009, which identified the planetary boundaries (PB) of various "*anthropogenic perturbations of critical Earth-system processes*" (Steffen et al., 2015, p. 737), giving a comprehensive outlook to the current impact of human activities to the planet. These Earth-system processes are, therefore, identified as essential to the maintenance of the Earth System at a Holocene-like state. It is important to note that the PBs do not represent the biophysical thresholds or tipping-points of the Earth, rather they are to be treated as the up-streams or 'safe operating spaces' that already took the uncertainty risk as well as "*society's time to react to early warning signs"* into account (Steffen et al., 2015, p.738).

When Rockström et al. (2009) introduced the PBs, the framework were incompletely defined and did not consider the regional-level heterogeneity of certain boundaries. However, six years after the introduction, Steffen and his colleagues, including Rockström, made an update and revision on the framework , "*with a focus on the underpinning biophysical science, based on targeted input from expert research communities and on more general scientific advances over the past 5 years*" (Steffen et al., 2015, p. 737).

In the latest version, Steffen et al. (2015) defined 9 essential PB(s) in according to different Earth-system processes, that need to be respected in order to sustain the current condition of the Earth system. These boundaries are (1) Biosphere integrity, (2) Climate Change, (3) Land-system change, (4) Freshwater use, (5) Biogeochemical flows (Phosphorus-Nitrogen), (6) Ocean acidification, (7) Stratospheric ozone depletion, (8) Atmospheric aerosol loading, (9) Introduction of novel entities. They also updated the quantification for most of the PB(s), showing the updated currently known condition in comparison to each safe-operating limit of the PBs. Moreover, Steffen et al. further improve the previous PB-framework by introducing a two-tier approach as well as proposing a regional level quantitative boundary for some of PBs – land-system use, freshwater use, and phosphorus flow – in order to account *regional-level heterogeneity* (Steffen et al., 2015, p. 737).

Table 1 shows the updated version of the PB, with updated control variables and their current values. It is important to note that the term 'currently known value' that they used for each control variable does not represent the present value. In fact, for each boundary, the currently known value was chosen from the most validated and up-to-date scientific data that the authors could find.

Table 1: The updated control variables and their current values, along with the proposed boundaries and zones of uncertainty, for all nine PB(s). (Steffen et al., 2015, p.740)

Earth-system process	**Control variable(s)**	**Planetary boundary**	**Currently known value of control variable**
Climate change	Atmospheric CO_2 concentration (ppm)	350 ppm CO_2 (350-450 ppm)	398.5 ppm CO_2
	Energy imbalance at top-of-atmosphere, $W{\bullet}m^{-2}$	+1.0 Wm^{-2} (+1.0-1.5 Wm^{-2})	2.3 Wm^{-2} (1.1-3.3 Wm^{-2})
Change in biosphere integrity	Genetic diversity: Extinction rate	< 10 E/MSY (10-100 E/MSY) but with an aspirational goal of ca. 1 E/MSY (the background of extinction loss). E/MSY = extinctions per million species-years	100-1000 E/MSY
	Functional diversity: Biodiversity Intactness Index (Note: These are interim control variables until more appropriate ones are developed)	Maintain BII at 90% (90-30%) or above, assessed geographically by biomes/large regional areas (e.g. southern Africa), major marine ecosystems (e.g. coral reefs) or by large functional groups	84%, applied to southern Africa only
Stratospheric ozone depletion	Stratospheric O_3 concentration, DU	<5% reduction from pre-industrial level of 290 DU (5%-10%), assessed by latitude	Only transgressed over Antarctica in Austral spring (~200 DU)
Ocean acidification	Carbonate ion concentration, average global surface ocean saturation state with respect to aragonite	≥ 80% of the pre-industrial aragonite saturation state of mean surface ocean, including natural diel and seasonal variability (≥80% - ≥70%)	~84% of the pre-industrial aragonite saturation state
Biogeochemical flows: (Phosphorus and Nitrogen cycles)	Phosphorus (Global): Phosphorus flow from freshwater systems into the ocean	11 Tg P yr^{-1} (11-100 Tg P yr^{-1})	~22 Tg P yr^{-1}
	Phosphorus (Regional): Phosphorus flow from fertilizers to erodible soils	6.2 Tg yr^{-1} mined and applied to erodible (agricultural) soils (6.2-11.2 Tg yr^{-1}). Boundary is a global average but regional distribution is critical for impacts.	~14 Tg P yr^{-1}

	Nitrogen (Global): Industrial and intentional biological fixation of Nitrogen	62 Tg N yr^{-1} (62-82 Tg N yr^{-1}). Boundary acts as a global 'valve' limiting introduction of new reactive N to Earth System, but regional distribution of fertilizer N is critical for impacts.	~150 Tg P yr^{-1}
Land-system change	Global: Area of forested land as % of original forest cover	Global: 75% (75-54%) values are a weighted average of the three individual biome boundaries and their uncertainty zones	62%
	Biome: Area of forested land as % of potential forest	Biome: Tropical: 85% (85-60%) Temperate: 50% (50-30%) Boreal: 85% (85-60%)	
Freshwater use	Global: Maximum amount of consumptive blue water use in river run-off (km^3 yr^{-1})	Global: 4000 km^3yr^{-1} (4000-6000 km^3yr^{-1})	~2600 km^3 yr^{-1}
	Basin: Blue water withdrawal as % of mean monthly river flow	Basin: Maximum monthly withdrawal as a % of mean monthly river flow. For low-flow months: 25% (25-55%); for intermediate-flow months: 30% (30-60%); for high-flow months: 55% (55-85%)	
Atmospheric aerosol loading	Global: Aerosol Optical Depth (AOD), but much regional variation		
	Regional: AOD as a seasonal average over a region. South Asian Monsoon used as a case study	Regional: (South Asian Monsoon as a case study): anthropogenic total (absorbing and scattering) AOD over Indian subcontinent of 0.25 (0.25-0.50); absorbing (warming) AOD less than 10% of total AOD	0.30 AOD, over South Asian region
Introduction of novel entities	No control variable currently defined: N/A	No boundary currently identified, but see boundary for stratospheric zone for an example of a boundary related to a novel entity (CFCs)	

2.2.1 Climate change

In climate change, the average CO_2 concentration of 350 ppm was set as the first planetary boundary, based on the equilibrium sensitivity analysis of climate to greenhouse gas forcing (Hansen et al., 2008) and the observation of the relationship between the CO_2 concentration and natural phenomenon in the past and present (Cazenave, 2006; Hansen et al., 2008; Johannessen, 2008). Additionally, the change in radiative forcing of +1 Wm^{-2} was set as another boundary, as it corresponds to global mean temperature increase of slightly less than 1 Celsius (Rockström et al., 2009). As for the current value of both control variables, the authors used the annual average CO_2 concentration for 2014 (399 ppm) (National Oceanic and Atmospheric Administration), n.d.) and the increase in top-of-atmosphere radiative forcing in 2011 relative to 1750 (+2.3 Wm^{-2}) (Intergovernmental Panel on Climate Change (IPCC), 2013).

2.2.2 Biosphere integrity

In change in biosphere integrity, Steffen et al. suggested two aspects to capture for the earth system, which are genetic diversity and the biosphere's functional diversity. The first aspect determines the capacity of the biosphere to survive and adapt under the abrupt or slow abiotic change, while the second one "*measures the loss of biodiversity components at both global and biome ecosystem levels*" (Steffen et al., 2015, p. 741). For genetic diversity, Steffen et al. mentioned that the phylogenetic species variability (PSV) (Mace et al., 2014) would be an appropriate control variable. However, since there has yet to be any global data for PSV available, the authors retained the global extinction rate as an interim control variable, despite its inaccuracy and time lag. The chosen data for the 'currently known value' is an (imperfectly) known extinction rate of well-studied organisms over the past few million years (Barnosky et al., 2011). For functional diversity, they proposed the Biodiversity Intactness Index (BII) (Scholes & Biggs, 2005) as the control variable for the regional and global scale. The index assesses the change in population abundance due to human impact (using preindustrial era abundance as the reference point) (Steffent et al., 2015, p.741). However, it is questionable whether the BII was an appropriate control variable or not, because Steffen et al. admitted themselves that there is still a lack of relationship between the index and the earth system's response (ibid.), and also the current application of BII was only available in southern Africa region, not global.

2.2.3 Stratospheric ozone depletion

In stratospheric ozone depletion, Steffen et al. kept the control variable – O_3 concentration in Dobson Units (DU) – and boundary of 275 DU as original. Although the particular boundary was transgressed over the Antarctica region, as the concentration decreases down to about 200 DU in the past (British antarctic survey, 2013), the number has been steady for about 15 years and is expected to rise as the ozone hole is repaired, and human began to phase out of ozone-depleting substances.

2.2.4 Ocean acidification

In ocean acidification, its condition is linked with the planetary boundary of climate change – atmospheric CO_2 concentration – as the gas could be absorbed to the ocean through "*dissolution into seawater, and uptake of carbon by marine organisms*" (Rockström et al., 2009, p.12). The addition of CO_2 to the ocean would increase the acidity of the surface seawater (hydrogen concentration), which would in turn decrease carbonate concentration in the ocean. Consequently, this change primarily affects the biota (e.g. corals and mollusks) that use carbonate ions in seawater to produce calcium carbonate shell/structure (aragonite) (ibid.). Therefore, Rockström et al. (2009) chose the carbonate ion concentration of the average global surface ocean saturation state with respect aragonite as the control variable, with an interim state of more than 80% of the pre-industrial aragonite saturation state as the first estimate of the planetary boundary (ibid., p. 13). In addition to this, Steffen et al. (2015) did not find new evidence to suggest the new boundary. Accordingly, the current saturation state of aragonite (2007) is equal to 84% of the pre-industrial time (Guinotte & Fabry, 2008), and the number would not transgressed the 80% boundary if the 350 ppm of atmospheric CO2 boundary were to be respected

2.2.5 Biogeochemical flow

In biogeochemical flow, although Steffen et al. pointed out the necessity of having a comprehensive planetary boundary that includes more element flow into account, the flow Phosphorus (P) and Nitrogen (N) are still the only focuses of their study (Steffen et al., 2015).

2.2.5.1 Phosphorus flow

For P, the authors proposed two-level approach of study; one was for the global scale and another was for the regional context. In the global-scale, they retained the original global-level control variable suggested by Rockstorm et al. (2009), who based the decision from the study about the link between the oscillations of the phosphorus biogeochemical cycles and the periodic mid-Cretaceous oceanic anoxic events (OAE) (Handoh & Lenton, 2003), which identified the influx of P to the ocean as a key driver of OAE. Accordingly, they also retained the low estimate of 'pre-agricultural' P inflow to the ocean – 1.1 Mt yr^{-1}) (ibid.) – as the original planetary boundary.

In the regional scale, Steffen et al. proposed the flow of fertilizers-P to erodible soil as the control variable, based on the study of Carpenter and Bennett who raised a concern on the lack of the planetary boundary for freshwater eutrophication due to P flow (Carpenter & Bennett, 2011). Accordingly, the planetary boundary was made by subtracting the global flow of P to erodible soil (26.2 Tg yr^{-1}) with the global release of P to surface soil due to weathering (15-20 Tg yr^{-1}), and as a result, the influx of fertilizers-P to erodible soil is 6.2 Tg yr^{-1} with a zone of uncertainty of 6.2-11.2 Tg yr^{-1}. Although it is arguable that the appropriate control variable would be the flow of P from soil to the freshwater system, however, Steffen et al. consider the component to be "*more difficult to measure than the application of P to soils and is also less amenable to management control*" (Steffen et al., 2015b, p.738). As for the currently known value, the authors use the global rate of application of P in fertilizers to croplands (14.2 Tg P yr^{-1}) – the key factor to the transgression of the boundary – from the studies on the global changes of phosphorus cycles in agriculture (Bouwman et al., 2013; MacDonald, Bennett, Potter, & Ramankutty, 2011)

2.2.5.2 Nitrogen flow

Unlike P, Steffen et al. only proposed the control variable of N flow at the global scale, which was derived from the De Vries et al.'s suggestion to use the combined input of N from intended human fixation processes (De Vries, Kros, Kroeze, & Seitzinger, 2013) – this included the anthropogenic industrial fixation of nitrogen from atmospheric N_2 via the Haber-Bosch process, and intended biological N fixation. Accordingly, they also adopted the planetary boundary range of intentional N-fixation to the agricultural system from the same study, which was about 62-82 Tg P yr^{-1} (ibid). As for the planetary boundary, the authors identified the boundary by applying the P boundary to the average N:P ratio in growing plant tissues, which was 11.8:1 (Greenwood et al., 2008). It is important to note that the ratio is actually higher than the ratio of global N:P input (based on N & P fertilizer application rates and agricultural fixation) as well as the global N:P loss ratio of the year 2000 (Bouwman et al., 2013). And by adding the room uncertainty, the suggested planetary boundary for N flow is 150 Tg N yr^{-1}.

2.2.6 Land-system change

In land-system change, the Earth system's process was divided into the global and biome level. Steffen et al. replaced the control variable of the amount of cropland to the amount of forest cover remaining, as the three major forest biomes (tropical, temperate, and boreal) has stronger influence in land surface-climate (Snyder, Delire, & Foley, 2004). While the planetary boundary for the global level was suggested based on the real estimates from Snyder et al. (ibid.), the boundary for the three forest biomes were proposed as a provisional boundary base on sensitivity studies (Snyder et al., 2004; West et al., 2011), except Tropical forest, where supporting studies that a threshold of land-cover change exists (Good et al., 2013; Hirota et al., 2011; Oyama & Nobre, 2003). The current status of the control variable at the global level was calculated using the ESA GlobCover 2009 database to estimate current forest cover.

2.2.7 Freshwater use

In freshwater use, Steffen et al. did not change the control variable for the global scale, neither its current value identified in the previous study (Rockström et al., 2009). According to the supplementary information in Rockström et al.'s study, the authors identified two anthropogenic pressures that may threaten the statibility of the flows in the global freshwater system: *"(i) human induced shifts in green water flows as a result of changes in precipitation (totals and patterns) and soil moisture generation, and (ii) human withdrawals of blue water impacting river flow dynamics*" (Rockström et al., 2009b, p. 13). Accordingly, the authors chose river depletion in the form of consumptive blue water use (the used blue water that does not return back to the resource system – it is either evaporated or embedded into a product) as a proxy for "*the full complexity of the highest risk for global water thresholds*" (ibid., p. 15), as it is also interlinked with the changes in green water (occuring upstream). They used the study of Postel (1998) and Shiklomanov & Rodda (2003) to respectively identify the availability of the river runoff, and the global withdrawal and use of runoff water. It is estimated that there are 12,500 km^3 of river runoff available for human appropriation (Postel, 1998), and that the global withdrawals of runoff water in the beginning of 21st century is about 4000 km^3yr^{-1}, of which 2600 km^3yr^{-1} is for consumptive use (Shiklomanov & Rodda, 2003). To identify the threshold of the consumptive use, they used the study from the UN comprehensive freshwater assessment (Lundqvist & Gleick, 1997) and the subsequent works (Alcamo et al., 2003; Vörösmarty, Green, Salisbury, & Lammers, 2000) which suggest that the withdrawal of runoff water should not exceed 40% of available blue water resources (5,000 km^3yr^{-1}), with the uncertainty range of more than 1000 km^3yr^{-1} (Vörösmarty et al., 2000). Thus, Rockström et al. proposed that the planetary boundary of consumptive blue water use (in river runoff) to be 4000-6000 km^3yr^{-1}.

Additionally, Steffen et al. also included the control variable for freshwater use at the basin level as well. They used the variable monthly flow (VMF) method to calculate the boundary

(Pastor, Ludwig, Biemans, Hoff, & Kabat, 2014), which took the intra-annual variability into account – high, intermediate, and low flow months.

2.2.8 Atmospheric aerosol loading

In atmospheric aerosol loading, Steffen et al. adopted aerosol optical depth (AOD) as the control variable. However, they did not provide the planetary boundary at the global scale as the particulate concentration in the atmosphere and its effect occur on regional basis (Rockström, et al., 2009a; Steffen et al., 2015a). Accordingly, Steffen et al., the south Asian monsoon as a case study, based on "the potential of widespread aerosol loading over the Indian subcontinent to switch the monsoon system to a drier state" (Steffen et al., 2015a, p.743).

2.2.9 Introduction of novel entities

In introduction of novel entities, Steffen et al. did not propose any control variable, neither the boundary, because there was not yet "*an aggregate, global-level analysis of chemical pollution on which to base a control variable or a boundary value*" (Steffen et al., 2015a, p. 744)

To summarize the PB-framework, as can be seen in **Table 1**, 4 out of 9 PB(s) have already been transgressed; these are Biosphere integrity, Biogeochemical flows, Climate change, and Land-system change. Particularly, the current values of the first two mentioned boundaries are already way beyond the zone of uncertainty (**Figure 7**) . As for the rest of non-transgressed boundaries, only three of them are safely defined below the boundary, while the other two – Introduction to novel entities and Atmospheric aerosol loading – their global level boundaries have yet to be defined, therefore, remain unknown.

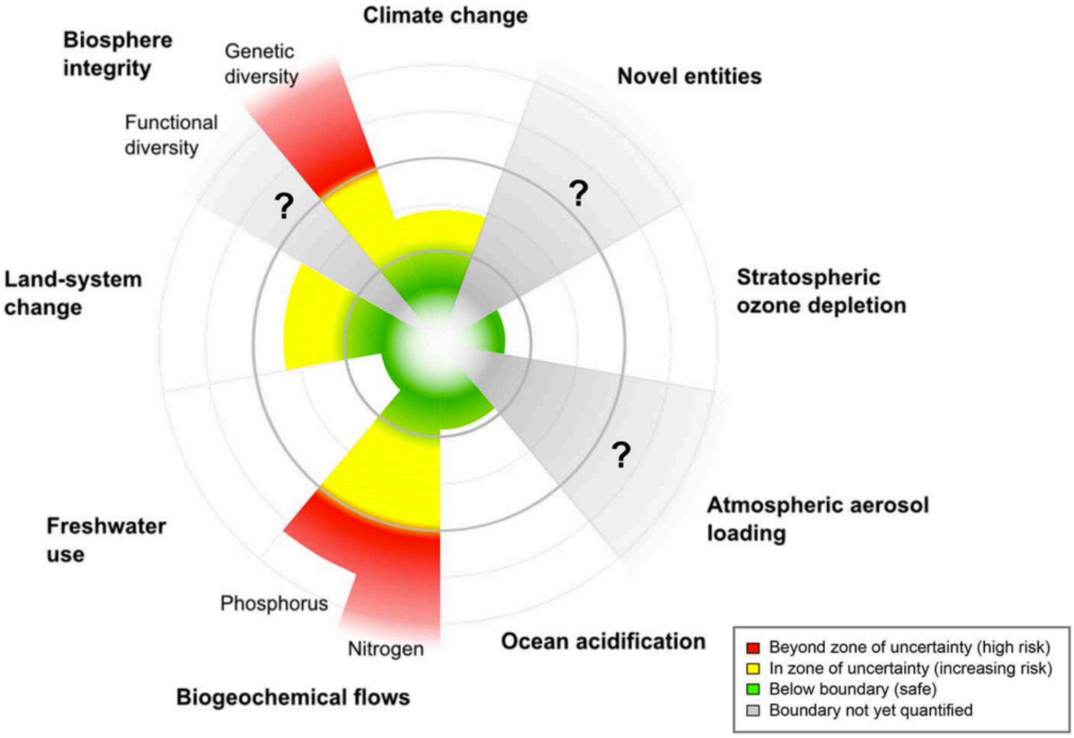


Figure 7: The current status of the control variables for seven of the nine PB(s). The green zone is the safe operating space (below the boundary), yellow represents the zone of uncertainty (increasing risk), and red is the high-risk zone. The PB itself lies at the inner heavy circle. The control variables have been normalized for the zone of uncertainty (between the two heavy circles); the center of the figure therefore does not represent values of 0 for the control variables. The control variable shown for climate change is atmospheric CO2 concentration. (Steffen et al., 2015, p.741)

2.3 Developing impact-reduction target for a product under the PB-framework

The interesting notion between the PB and LCA framework is that they are two opposite sides of a coin. On one hand, the LCA is utilized to identify the value of environmental impacts in a product scale. On other hand, the PB-framework identify the impact in a global scale for different Earth Systems, and also the safe operating spaces for each of them. Therefore, researchers have been trying to integrate the PB-framework in LCA context for the past several years, in order to finally align the impact of specific human activities to the environmental sustainability of the planet (Bjørn & Hauschild, 2015; Fang et al., 2015; Sala & Goralczyk, 2013; Sandin et al., 2015; Tuomisto et al., 2012).

In 2015, Sandin and his colleagues published a study "*proposing* [the first] *general procedure for using the knowledge about current global impacts in relation to the PBs, for setting impact-reduction targets at the product scale*" (Sandin et al., 2015, p.1686) – which in this thesis the procedure is called Sandin's procedure. Additionally, they also applied the procedure to a case-study of Swedish clothing consumption in order to test the outcome. The objective was to identify the impact-reduction targets of the Swedish clothing consumption under the time horizon of 2050, in order to evaluate the potential of an array of suggested interventions for impact reduction. Accordingly, the year 2050 was chosen as the time horizon because, according to Roos et al., it allows for the development and large-scale diffusion of impact-reduction the interventions suggested today (Roos, Sandin, Zamani, & Peter, 2015). Moreover, they also argues that 35 years is a reasonable time horizon for strategic development in market segment transformation (Grübler, 2003).

Based on Sandin's procedure, the impact-reduction target of a product is developed by allocating the global impact-reduction target to the specific market segment of the studied product, and to the geographical scope in any process within the studied product-system and time horizon. The procedure can be mathematically described as follow:

$$\mathbf{RT_{X,Y,Z} = 100-(100-RT_X) * A_{market,\,Y} * A_{region,\,Z}}$$

- "$\boldsymbol{RT_{X,Y,Z}}$ *is the impact-reduction target (in %) for a product under the geographical scope* ***Z*** *in impact category* ***X,*** *belonging to global market segment* ***Y*** *– i.e. how much impact of a specific product under specific market segment and specific geographical scopes in a certain impact category must be reduced (in %) within the chosen time horizon."* (Sandin et al., 2015, p. 1686)

- "$\boldsymbol{RT_X}$ *is the necessary reduction of the global impact in impact category* ***X*** *according to the current knowledge about PBs (in % of current annual global impact)*" (Sandin et al., 2015, p. 1686)

- "[$\mathbf{A_{market,\,Y}}$] *is the factor for allocating the share of the globally allowed annual impact to global market segment* ***Y***" (Sandin et al., 2015, p. 1686)

- “[$\mathbf{A}_{\mathbf{region},\,Z}$] *is the allocation factor reflecting the allowed impact for the residents of the country **Z** versus the rest of the global population.*” (Sandin et al., 2015, p. 1686)

Therefore, based on the above equation, by identifying the global impact reduction target ($\boldsymbol{RT_x}$), and the two allocation factors ($\boldsymbol{A_{market,\,Y}}$ and $\boldsymbol{A_{region,\,Z}}$), the impact-reduction targets of a product can be developed.

2.3.1 The global impact-reduction targets (RT_X)

Table 2 (below) shows the global impact-reduction targets identified by Sandin et al. (2015) in respect to the PB(s). Sandin and colleagues used the quantitatively updated PBs of various Earth systems in Steffen et al. (2015) as their main input. They selected several PBs “*that were deemed feasible to use for setting global impact-reduction targets, that relate to impact categories that are commonly studied in LCAs, and that are potentially relevant to* [the case study of Swedish clothing consumption]” (Sandin et al., p.1687). Therefore, the excluded control variables means that they are either (i) difficult to interpret in term of a global impact-reduction as they are described in terms of an absolute state and not a rate of intervention; (ii) the quantification is not available; or (iii) that they have low relevance to the studied product which is clothes. Consequently, four out of nine PB(s) are excluded from their study; these are (1) Introduction of novel entities (ii), (2) Stratospheric ozone depletion (i & iii), (3) Atmospheric aerosol loading (i), and (4) Ocean acidification. For the exclusion of ocean acidification, Sandin et al. argued that the Earth system process has never been studied in LCA, despite the fact that it has been acknowledged as a contributing factor to the end point impact of biodiversity loss (Curran et al., 2011). Furthermore, since the Earth system is directly influenced by the atmospheric CO_2 concentration, its boundary would not be transgressed if the climate change boundary were respected (Steffen et al. 2015).

Table 2: A set of global impact-reduction targets developed by Sandin and his colleagues based on the current understanding of the planetary boundary, according to Steffen et al. (2015). (Sandin et al., 2015, p.1688)

Earth systems	Control variables for quantifying the PB	Related impact categories in LCA context	Global targets for impact reduction by the PB
Climate change	(i) Atmospheric carbon dioxide concentration (ii) Energy imbalance at top-of-atmosphere	Climate change (Global warming potential)	100%
Interferences with the nitrogen cycle (Biogeochemical flow)	Annual rate of industrial and intentional biological fixation of nitrogen	Eutrophication, marine eutrophication, terrestrial eutrophication, terrestrial acidification	59%
Interferences with the phosphorus cycle (Biogeochemical flows)	(i) Annual rate of phosphorus flowing into oceans (ii) Annual rate of phosphorus flow from fertilizers to erodible (agricultural) soils	Eutrophication, freshwater eutrophication	56%
Freshwater use	Annual consumptive blue water use (global control	Freshwater consumption	-54%

	variable; control variables are also suggested at the level of biomes)		
Land-system change	Area of forested land as percentage of original forest cover (global control variable; control variables are also suggested at the level of basins)	Land transformation (in particular transformation of forest land)	100%
Changes in biosphere integrity	(i) Species extinction rate (as a control variable for genetic diversity) (ii) Biodiversity Intactness Index (as a control variable for functional diversity)	Land occupation (midpoint), land transformation (midpoint), biodiversity loss (endpoint)	99%

2.3.1.1 Climate change

In climate change, the PB can be translated directly to the LCA impact category of climate change. Sandin et al. developed the global impact-reduction target based on the facts that the two planetary boundaries have already been transgressed (Steffen et al., 2015a), and that the value of two control variables – the atmospheric CO_2 concentration and the radiative forcing – are certain to rise for years to come (IPCC, 2013). As a result, they assume that *the net impact from greenhouse gas emissions and other stressors causing climate change must be reduced to zero by 2050,* [so that the values would] *reach the safe operating spaces* [350 ppm CO_2 and +1.0 Wm^{-2} (Steffen et al., 2015a)] *without risking further diminution of it*” (Sandin et al., 2015, p. 1687). Therefore, a 100% global impact-reduction target is suggested for climate change impact.

2.3.1.2 Interferences with the Nitrogen cycle

According to Sandin et al. (2015), the interferences with the Nitrogen cycle can be closely translated to marine eutrophication and terrestrial eutrophication (or acidification) in LCA impact categories. The authors use the planetary boundary and currently known value of the annual rate of industrial and intentional biological fixation of Nitrogen, which is the only control variable for Nitrogen flow (Steffent et al., 2015a), to calculate the global impact-reduction target.

Calculation: (150 – 62 Tg N yr^{-1}) / 150 Tg N yr^{-1} * 100% = 59%

2.3.1.3 Interferences with the Phosphorus cycle

As for the interferences with the Phosphorus cycle, Sandin et al. translated the Earth system to freshwater eutrophication in LCA context. Sandin et al. chose the regional-level control variable which is the annual rate of phosphorus flow from fertilizers to erodible (agricultural) soil (Steffen et al., 2015), to develop the impact-reduction target. The reason is because the result shows more drastic target than the first one, and also the control variable is chosen from the study that focuses on the planetary boundary of freshwater eutrophication (Carpenter & Bennett, 2011)

Calculation: (14 – 6.2 Tg N yr^{-1}) / 6.2 Tg N yr^{-1} * 100% = 56%

2.3.1.4 Freshwater use

For freshwater use, Sandin et al. translated the Earth system to freshwater consumption (Sandin et al., 2015). Accordingly, they use the global control variable of the Earth system, which is the annual consumptive blue water use, to develop the impact-reduction target. They explain that because their concern is "*the environmental impact of an entire market segment (clothing consumption in Sweden), for which the freshwater use throughout the life cycles are distributed over numerous biomes and basins in many countries"* (ibid., p.1688), it is suitable to use the global-level control variable to calculate.

Calculation: (2600 – 4000 km^3yr^{-1}) / 4000 km^3yr^{-1} * 100% = -54%

(Noted: since the current value of the variable has yet to transgress the limit – 4000 km^3 per year – the reduction target is shown in negative value)

However, for a specific product life cycle, with processes of known geographical location, whereas a more regional quantification of impact-reduction targets is possible, Sandin et al. suggest that their proposed procedure would have to be "*adopted to support such a regionalized interpretation of the PB framework*" (Sandin et al., 2015, p.1688)

2.3.1.5 Land-system change

For the land-system change, the PB can be related to Land transformation (in particular transformation of forest land) in LCA impact category. And similar to Freshwater use, Sandin et al. chose the global control variable for the same reason. Moreover, since the current area of forested land as % of original forest area is already lower than the boundary, the authors assume that there should never be any reduction in the value (Sandin et al., 2015). Therefore, the global impact-reduction target of the category is set as 100%.

2.3.1.6 Changes in biosphere integrity

For the change in biosphere integrity, Sandin et al. chose land occupation and transformation (midpoint), and biodiversity loss (endpoint) in LCA context as the most relevant impact categories. Accordingly, Steffen et al. (2015) proposed two control variables for the changes in biosphere integrity; these are species extinction rate and Biodiversity Intactness Index (BII). In translating this PB into a global target, Sandin et al. used the first variable to calculate the target as "*it reflects a rate of intervention, which is easier to interpret in terms of a target for impact reduction, compared to a control variable for an absolute state (which the second variable represents)"* (Sandin et al., 2015, p.1689)

Calculation: (1000 – 10 E/MSY) / 1000 E/MSY * 100% = 99%

2.3.2 The allocation factor for specific market segment ($A_{market, Y}$)

According to Sandin et al. (2015), when allocating the global impact-reduction targets to a specific market segment, it is arguable that certain market segment might have higher necessity to human needs (e.g. food segment), and, therefore, should have "*a right to a larger share of the allowed impact*" (ibid., p.1689) than the market segments that deem less essential. Products that are consumes for luxurious purpose, for example, should have less of a right to cause impact. However, it is difficult to determine whether the products of the specific market segment would have higher importance to human needs or not, as this depends on the ethical value of a person. Therefore, in order to handle the dilemma, Sandin et al. suggests three different perspectives for the identification based on three ethical perspectives towards how much share of impact should products in the specific market segment be allowed to cause in the future.

2.3.2 1 Perspective A: The segment has the right to cause the same share of impact

In Perspective A, the value of the products of the segment in the future remains unchanged, and, therefore, the products have the right to create the same share of impact as they do today. Additionally, this approach can also be applied to the perspective that views "*all market segments should have the same obligation to reduce impacts at the same share*" (Sandin et al., 2015, p.1689).

Thus, $\boldsymbol{A}_{market,\ Y} = 1$

2.3.2.2 Perspective B: The segment has the right to cause half the share of impact

In Perspective B, the products in the segment are perceived to be of less importance in fulfilling essential human needs than the average market segment in the future, and, therefore, should have "*a right to cause half the share of impact as they do today*" (Sandin et al., 2015, p. 1689).

Thus, $\boldsymbol{A}_{market,\ Y} = 0.5$

2.3.2.3 Perspective C: The segment has the right to cause twice the share of impact

In Perspective C, the products in the segment are perceived to be of higher importance to human needs than the average market segment in the future, and, therefore, should have "*a right to cause twice the share of the impact compared to their current share*" (Sandin et al., 2015, p. 1689).

Thus, $\boldsymbol{A}_{market,\ Y} = 2$

2.3.3 The allocation factor for specific geographical context ($\boldsymbol{A}_{region,\ Z}$)

Likes the allocation factor for specific market segment, allocating the allowed impact of the global market segment between the residents of the contextual country and the rest of the global population can be just as challenging, as it is also subjective to different ethical perspective. Sandin et al. explored these perspective in their study, by reviewing literatures related to the ethical principles about "*how to divide emission budgets between nations and regions, most often focusing on greenhouse gas emissions (e.g. Grasso, 2012; Knopf et al., 2012)*" (Sandin et al., 2015, p. 1689). As a result, four ethical principles are proposed as the approaches for identifying the allocation factor of specific geographical context. **Table 3** (below) describes the four ethical principles as originally explained by Sandin and his colleagues in their paper.

Table 3: List of ethical principles that Sandin and colleagues used to rationalize and allocate the allowed impact to specific geographical context. (Sandin et al., 2015, p. 1690)

Ethical principle	**Description**
Principle 1: Individual right	"*With this principle, the future (in our case: in 2050) allowed impact of the global market segment to which the studied product belongs (in our case: the global clothing market segment) should be split equally between all individuals in the world. The principle implies that populations with a relatively high per capita impact today should reduce their impact with a higher percentage.*" (Sandin et al., 2015, p. 1690)
Principle 2: Historical right of the regional market segment	"*This principle implies that the future allowed impact of the global market segment to which the studied product belongs should be allocated to the geographically delimited market segment that the study focuses on (in our case: Swedish clothing consumption) based on the current split. In other words, the studied regional market segment inherits the right to cause a certain share of the environmental impact of the global market segment to which it belongs.*" (Sandin et al., 2015, p. 1690)
Principle 3: Historical right of individuals in populations	"*This principle is similar to principle 2, but residents (instead of a market segment) of the region that the study focuses on inherit a certain right to cause environmental impact. For ex- ample, if Sweden today causes twice as much per capita impact as the global average, future residents of Sweden should likewise have the right to cause twice as much per capita impact as the global average. Thus, if the population increase of Sweden is slower than the global population increase, this principle will, compared to principle 2, allocate a smaller share of the future globally allowed impact to Swedish residents (or, in our case: the clothing consumption of Swedish residents)*" (Sandin et al., 2015, p. 1690)
Principle 4: Historical debt of individuals in populations	"*This principle applies the opposite mechanism to principle 3: if individuals of the region which the study focusses on cause more impact per capita than the global average, future residents of that region should be allowed to cause less impact than the global average. Thus, the principle aims at equality in terms of the cumulative impact of populations*" (Sandin et al., 2015, p. 1690)

The four equations below mathematically describe the ethical principles used to identify the allocation factor. $\boldsymbol{P_{GloCur}}$ and $\boldsymbol{P_{GloFut}}$ respectively represent the current and future (year 2050) global populations, while $\boldsymbol{P_{RegCur}}$ and $\boldsymbol{P_{RegFut}}$ respectively represent the current and future populations of the studied region. Lastly, $\boldsymbol{I_{Glo}}$ and $\boldsymbol{I_{Reg}}$ represent the global and regional average per capita impact in a given impact category, respectively.

2.3.3.1 Principle 1 "Individual Rights"

$$A_{region,Z} = \frac{P_{GloCur}}{P_{GloFut}} \times \frac{I_{Glo}}{I_{Reg}}$$

2.3.3.2 Principle 2 "Historical right of the regional market segment"

$$A_{region,Z} = \frac{P_{RegCur}}{P_{RegFut}}$$

2.3.3.3 Principle 3 “Historical right of individuals in populations”

$$A_{region,Z} = \frac{P_{GloCur}}{P_{GloFut}} \times \frac{P_{RegCur}}{P_{RegFut}}$$

2.3.3.4 Principle 4 “Historical debt of individuals in populations”

$$A_{region,Z} = \frac{P_{GloCur}}{P_{GloFut}} \times \frac{P_{RegCur}}{P_{RegFut}} \times \left(\frac{I_{Glo}}{I_{Reg}}\right)^{2}$$

3. Research methodology

As already mentioned in Chapter 1, to answer the main research question, two separated study had to be conducted; one was the life cycle assessment (LCA) of cotton clothes in the Netherlands; and another was the development of impact-reduction target of the products throughout the lifecycle based on Sandin's procedure.

In this chapter, the methodology of both studies are described. Accordingly, the description is going to be divided into two parts:

Part 1: the LCA of cotton clothes in the Netherlands;

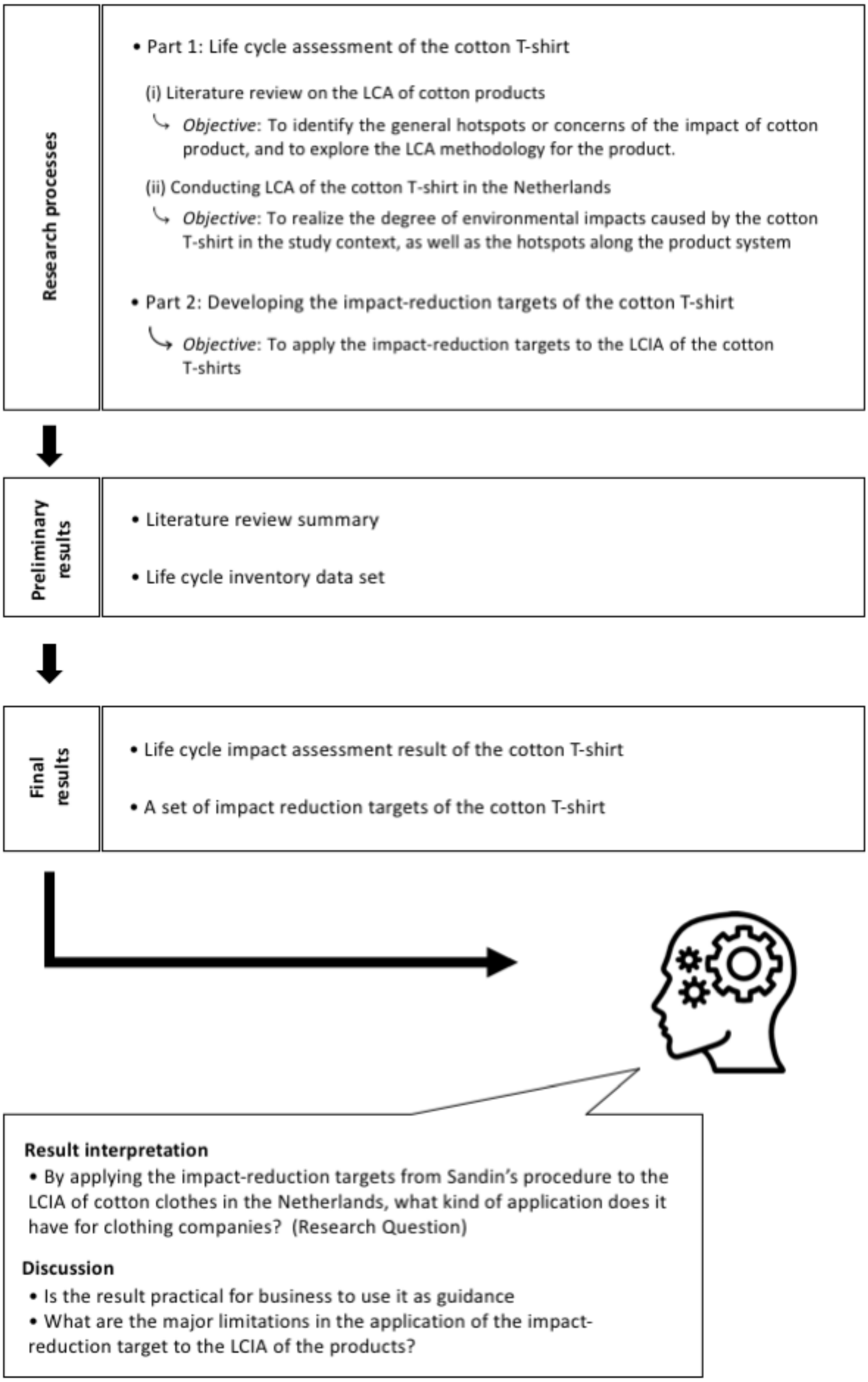
Part 2: the development of impact-reduction target of the cotton clothes.

In Part 1, the environmental impact of cotton clothes in the Netherlands was assessed using LCA framework (M. Hauschild et al., 2011) – see Section 2.1. The assessment began by reviewing literature related to the LCAs of cotton products, in order to understand what were the significant environmental impacts of the cotton products, and what were the hotspot activities that contribute to the impacts. After that, the LCA of the cotton clothes was conducted. Thus, there were three outputs from the research in Part 1: (1) The literature review and (2) the lifecycle inventory were the preliminary results that were used to conduct LCA of the cotton T-shirt, while (3) the LCIA of product was the final result.

In Part 2, the impact-reduction targets of the cotton clothes were developed using Sandin's procedure – see Section 2.3. The impact-reduction targets were the only result in this part.

By combining the (final) results of the two studies, which were the lifecycle impact assessment and the impact-reduction targets of the cotton T-shirts, the research question was answered, and the result was discussed.

Figure 8 (next page) illustrates the research processes in this master thesis.



- Part 1: Life cycle assessment of the cotton T-shirt
  - (i) Literature review on the LCA of cotton products
    - *Objective*: To identify the general hotspots or concerns of the impact of cotton product, and to explore the LCA methodology for the product.
  - (ii) Conducting LCA of the cotton T-shirt in the Netherlands
    - *Objective*: To realize the degree of environmental impacts caused by the cotton T-shirt in the study context, as well as the hotspots along the product system
- Part 2: Developing the impact-reduction targets of the cotton T-shirt
  - *Objective*: To apply the impact-reduction targets to the LCIA of the cotton T-shirts

- Literature review summary
- Life cycle inventory data set

- Life cycle impact assessment result of the cotton T-shirt
- A set of impact reduction targets of the cotton T-shirt

Result interpretation

- By applying the impact-reduction targets from Sandin's procedure to the LCIA of cotton clothes in the Netherlands, what kind of application does it have for clothing companies? (Research Question)

Discussion

- Is the result practical for business to use it as guidance
- What are the major limitations in the application of the impact-reduction target to the LCIA of the products?

Figure 8: Summary of research methodology

3.1 Literature review on the environmental impact assessment of cotton products

The purpose of the literature review was to explore the current understanding regarding the environmental impact of cotton products, and to figure out to what extend had the topic been studied in the academic realm. Additionally, the result of the review was also used to support the LCA study of the cotton T-shirt.

In term of data collection, all the reviewed literatures were going to collected from publicly online sources (i.e. academic journals and online websites), and all the LCA studies must involve 100% cotton products.

The figure below shows the questions and steps used to identify whether a literature was relevant the case-study in this master thesis or not, and also to filter for valuable information for conducting the LCA.

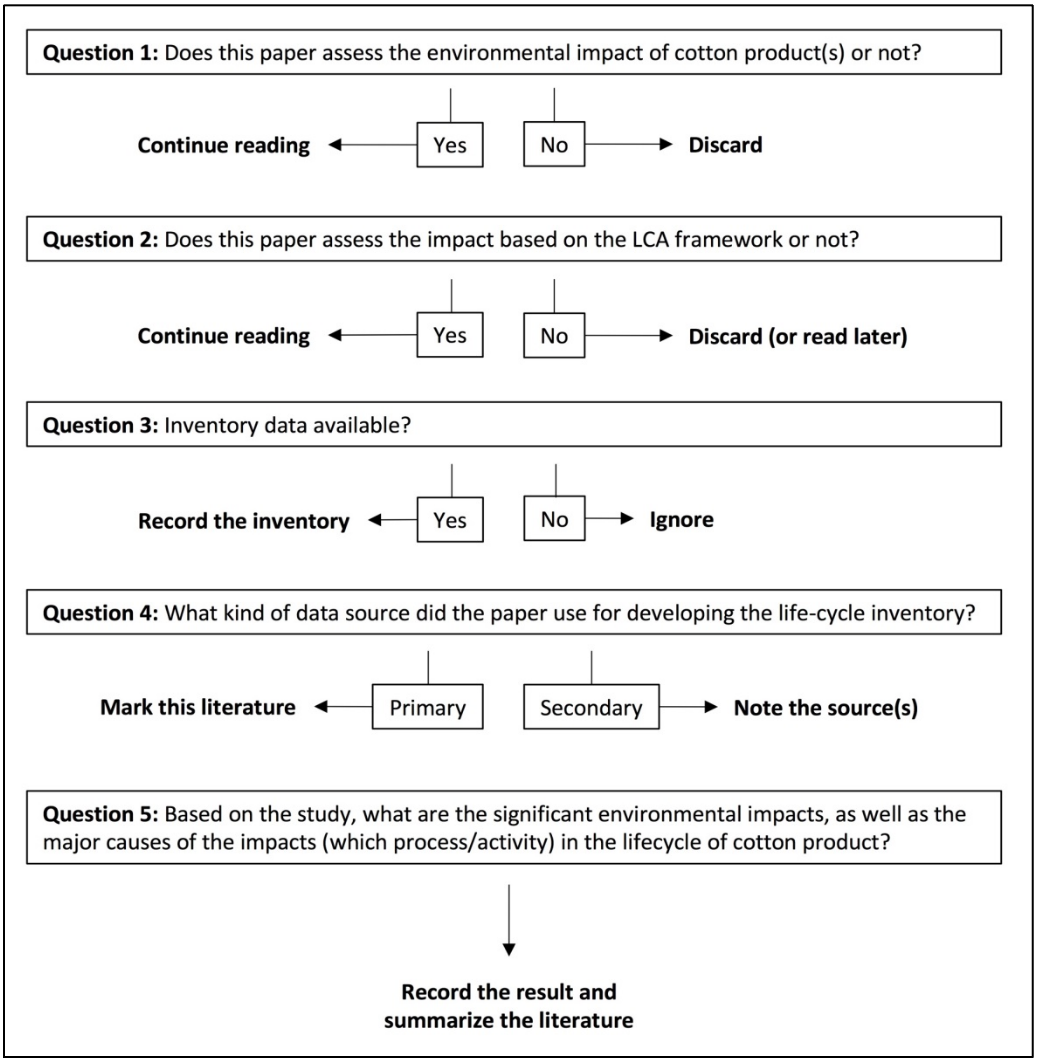


Figure 9: Literature review procedure

The result of the literature review is a summary of 10 literatures that highlight the common, yet significant environmental impacts from the lifecycle of cotton products. They also highlight the hotspot activities/processes. This summary can be found in the preliminary result section (Section 4.1).

Furthermore, since some of the literatures also provided useful inventory dataset, particularly those with data collected from primary sources, they were used to support the development of the lifecycle inventory for the LCA of the cotton T-shirt as well.

3.2 LCA of the cotton T-shirt

Once a comprehensive understanding on the environmental impact and the LCA characteristics of cotton products was made through literature review, the LCA of cotton clothes in the Netherlands was conducted.

3.2.1 Goal and scope definition

3.2.1.1 Goal of the study

The objective of this LCA was to realize the environmental impact of cotton clothes in the Netherlands and to apply the LCIA result with the impact-reduction targets, developed using Sandin's procedure, in order to explore possible application for clothing companies to improve the sustainability performance along their business's value chain. Correspondingly, two cotton clothes with different source of fiber were chosen for the study; one of them used the cotton fibers produced in the United States, while another used the fibers produced in China. The production of the two countries altogether covered 40% of the global cotton production (Statista, 2017). The reason for assessing both products was because, due to the complexity of cotton supply-chain (Masson et al., 2007), it was difficult to pinpoint the actual source of cotton fibers – especially when this thesis had no collaboration with any clothing company. The aim of studying the products with fiber sources from two major countries, therefore, was to cope with the inaccuracy issue of the fiber source.

To achieve the LCA objective, the following steps were set:

1. Identifying the context of the two cotton clothes (from cradle to grave) – i.e. scope, product system, functional unit;
2. Developing the life cycle inventory of both product system;
3. Assessing the environmental impact of both products.

3.2.1.2 Scope of the study, product system, and functional unit

Functional unit and reference flow

In this LCA study, a cotton T-shirt was chosen as the studied cotton cloth. The reason for choosing the type of cloth was because, according to Beton et al. (2014) who conducted LCA in collaboration with the European Union on clothing products of various fiber type and clothing categories in Europe, T-shirt was one of the most consumed clothing items in Europe; about 55% of T-shirts consumed in the region are made from cottons. Additionally, the average weight of a cotton T-shirt was assumed to be 0.21 kg (ibid.).

The functional unit of the product is a 100% white, short-sleeved cotton T-shirt, with the size of 180/96A (shoulder width: 50 cm; chest width: 110 cm; sleeve length: 20 cm; garment length: 70 cm) and the fiber density of 200 g/m^2 (Zhang, Liu, Xiao, & Yuan, 2015). The product is assumed to be worn for casual occasion regularly for 1 year before it is disposed away (Laursen et al., 2007). Accordingly, the product is assumed to be washed and tumbled dried for 50 cycles (ibid.) and 12 cycles (Beton et al., 2014) respectively during the period of use.

Product systems of the two cotton clothes

In order to define the product systems of the case study, extra literature review (aside from the LCA of cotton products) was conducted in order to identify the context of the two clothing products. These identification included, the consumer caring behavior on the T-shirt, the distance of the product distribution, and the textile waste treatment method in the Netherlands. Together with the LCA literature review (see Section 4.1), the product system of the two cotton products were developed.

The life-cycle of the cotton cloth from cradle to grave were generally divided into five main phases: (1) Fiber production, (2) Fabric manufacturing, (3) Product distribution, (4) Product use, and (5) Product disposal.

In fiber production, cotton fibers were cultivated, harvested and separated from cotton seeds through ginning process. As already mentioned, two locations were chosen as the production sources – the United States and China. The major environmental concerns in this phase were water depletion and chemical consumption through the use of pesticides and artificial fertilizers (Muthu, 2014).

In the second phase, the procured cotton fibers undergone a fabric manufacturing process which generally comprised of yarn spinning, knitting (or weaving), dyeing, and making-up of garments (Zhang et al., 2015). Cotton fibers of both products were assumed to be transported to the manufacturing site in China. This choice of the country was made upon the 2015's data of clothing imports in the Netherlands, in which China had the highest share of imports by almost 20% (World Integrated Trade Solution (WITS), 2015). Since the whole operation required the use of machinery, the process had high energy consumption and greenhouse gases emission (Baydar et al., 2015). Chemical substances like soaps and detergents were also consumed in some of the activities; it thus raised a concern on freshwater eutrophication. Additionally, a small amount of fiber or fabric was lost throughout the manufacturing process (Zhang et al., 2015).

Once the product were made and packed, they were distributed to retailer and sold to consumers. During the use phase, the product was regularly washed (and dried in some occasions) until they were disposed away as wastes. In the Netherlands, these wastes were treated mostly through incineration with energy recover; some were reused as second-hand clothing or insulation (Dutch Waste Management Association, 2013; Maldini et al., 2017). The use phase usually had the highest amount of impact than any other phases because of the extensive use of electricity, water and washing detergents over a period of time (Cotton Incorporated, 2012; Levi Strauss & Co., 2015).

In summary, based on the descriptions in the above paragraphs, the product systems of the two cotton T-shits are illustrated in **Figure 10**.

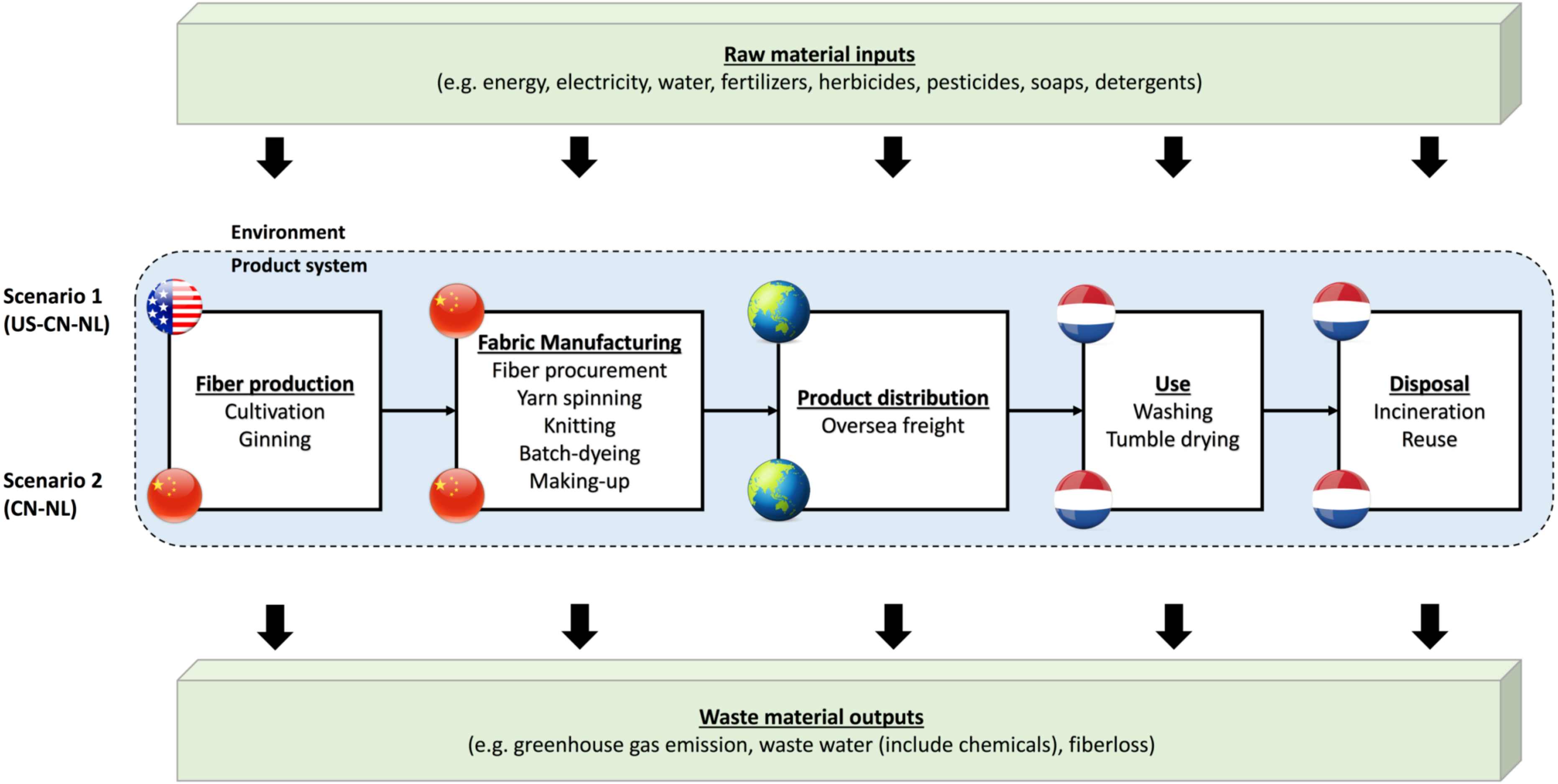


Figure 10: Product system of the life-cycle of the cotton T-shirt of two LCA scenarios. The dotted line represents the system boundary between the product system and the environment. The only different in the system between Scenario 1 (US-CN-NL) and Scenario 2 (CN-NL) is the location of fiber production; Scenario 1 has the United States (US) as the location, while Scenario 2 has China (CN).

Scope of impact assessment

Based on the result of the literature review, four (midpoint) impact categories were highlighted as major environmental concerns for the LCA of the cotton T-shirt; these were climate change, freshwater consumption, freshwater eutrophication, and eco-toxicity (Beton et al., 2014; Cotton Incorporated, 2012; Zhang et al., 2015). The scope of impact assessment in this thesis, therefore, covered the aforementioned categories, except for eco-toxicity. The reason for excluding the category was because the planetary boundary of 'the introduction to novel entities', which was the most relevant boundary to the impact category, had yet to be quantified by the scientists (Steffen et al., 2015a). Hence, it was not useful to include the impact category into the study.

Accordingly, ReCiPe model was chosen as the impact assessment method because its midpoint impact indicators covered all the scope of impact assessment (though climate change is expressed in the term of global warming potential). The impact assessment was conducted using Simapro software.

3.2.2 The development of life cycle inventory (LCI)

Since the goal was to assess the current environmental impact of a cotton T-shirt, the chosen LCI modelling framework for the study was attributional modelling framework, whereas the inventory of all processes of the system was developed as they occurred. The result of the LCI analysis were shown as the inventory dataset for the whole lifecycle of the cotton T-shirt, which can be found in the preliminary result (Section 4.2).

Table 4 shows the spatial and technological contexts of the inventory data in each phase of the product system.

Table 4: The spatial and technological context of the inventory data in each phase of the product system

Phase	Spatial context	Technological context
Fiber production	The United States or China (depends on the scenario)	Retrospective technology
Fabric manufacturing	China	Retrospective technology
Distribution	Oversea	Retrospective technology
Use	The Netherlands	Currently used technology (see Section 4.2.4)
Disposal	The Netherlands	Standard treatment

3.2.3.1 Data collection method

In data collection, the secondary sources was used to develop the lifecycle inventory. These sources were from publicly published LCA papers of cotton clothes, online information, and a well-known LCA database – Ecoinvent in Simapro software. The data from Ecoinvent was used as the main inventory for each process; the chosen inventory had to represent as close to the LCA context as much as possible. Accordingly, some inventory were modified through either quantification adjustment or change of input/output, based on the LCA literatures and online website, in order to fit the context of the LCA study. The LCA literatures used for the modification were chosen under two specific criteria: (1) the context of the study must be related to the context of this LCA study, and (2) the study must provide an inventory data that was compiled using primary data sources as part of its references. Additionally, it is important to clarify that the collected data from online information (e.g. websites, reports) were not used to build the inventory data; they were rather used to develop assumptions of the feature of the process, for example, the quality of washing machine and the distance of oversea shipping between ports.

The compiled inventory data for the whole lifecycle of the cotton T-shirt of the two scenarios, including its description and references, can be found in the preliminary result Section 4.2.

3.3 Developing the impact-reduction target of the cotton T-shirt.

In this study, Sandin's procedure was used to develop the impact-reduction target of the cotton T-shirt from the PB context. Accordingly, the procedure can be mathematically described as follow (Sandin et al., 2015):

$$\mathbf{RT_{X,Y,Z} = 100\text{-}(100\text{-}RT_X) * A_{market,\,Y} * A_{region,\,Z}}$$

To verbally explain, the impact-reduction target of a product can be developed by, first of all, identifying the global impact-reduction target (in %) for each PB ($\mathbf{RT_X}$), in order to identify globally allowed impact (%). Then, the identified globally allowed impact is allocated in according to specific market that the product belongs ($\mathbf{A_{market,\,Y}}$), and to the geographical context it is located ($\mathbf{A_{region,\,Z}}$). Several perspective and ethical principle were used to help with the allocations (see Section 2.3.2 and 2.3.3). Finally, the allocated, allowed impact (%) is then minus with 100%, which would result in the impact-reduction target (%) of the product for each geographical context.

3.3.1 Identifying the global impact-reduction target based on the PB-framework (RT_X)

In Sandin's procedure, Sandin et al. developed the global impact-reduction targets based upon the quantitative values and the boundaries of each control variable in the PB-framework (Sindin et al., 2015). They also suggested several matchings between the developed targets and some impact categories in LCA context. In this case-study, the global impact-reduction targets that were suggested to be related to the LCA impact categories of climate change, freshwater eutrophication and consumption were used as part of the variable to develop the impact-reduction targets of the cotton T-shirts (refer to **Table 2** in Section 2.3.1)

In the result section (section 5.2), all the impact-reduction targets of the two cotton T-shirts developed based on three different perspectives and four different ethical principles (suggested in Sandin's procedure) are shown in **Table 22-Table** 24. However, not all impact-reduction target of all the principles and perspectives were chosen to apply with the LCIA result of the cotton T-shirt (Part 1's result). The rationale for choosing suitable perspective for $\mathbf{A_{market,\,Y}}$ and suitable principle for $\mathbf{A_{region,\,Z}}$ are described the next two sub-sections.

3.3.2 Identifying the allocation factor for the market segment of cotton T-shirts ($A_{market,\,Y}$)

Sandin et al. (2015) suggested three perspectives for identifying the value of a product in a specific market segment, regarding how much share of impact should the product be allowed to cause in the future. In this thesis, Perspective B was chosen as the allocation approach for the cotton T-shirt, in which the product had the right to have only half the share of the globally allowed impact. The reason was because, although clothing could be considered as an essential product to human well-being, the current consumption behavior in the apparel market no longer treat cloth as a product of necessity, rather an accessory. Particularly, since the use of product in this LCA context is in the Netherlands whereas a Dutch person buys 46 items annually on average (Maldini et al., 2017). Thus, it is reasonable to justify the cotton T-shirt as the product of luxury.

Therefore, the allocation factor for the market segment of cotton T-shirts ($A_{market,\ Y}$) = 0.5

3.3.3 Identifying the allocation factor for the geographical contexts ($A_{region,\ Z}$)

Although Sandin et al. (2015) suggested four different allocation methods for the geographical context based on four ethical principles (see Section 2.3.3), not all principles were equally appropriate to be used. Principle 2-3 can be problematic when the multiple geographical locations (i.e. regions or nations) are involved because the allocation is unequally split between the regional areas that currently has high impact contribution and the regional areas with low impact contribution. As for Principle 4, according to Sandin et al. (2015), the equation of the principle was made from a rough proxy and should be further studied before putting it into practice. Thus, if there were no proper rationale behind the application of a certain ethical principle, they recommended Principle 1 as the default principle. Accordingly, the principle also had the history of having the consensus across all countries, particularly the least developed ones (EurSafe, 2012). Moreover, the principle was recommended by an international organization – the United Nations Framework Convention on Climate Change (UNFCCC) – for distributing the emission budget for greenhouse gases (Posner & Sunstein, 2009), which was one of the studied impacts in this thesis. Therefore, for this thesis, Principle 1 'Individual right' was chosen as the allocation approach.

Therefore, the allocation method for each geographical context in the two LCA context ($A_{region,\ Z}$) is mathematically described as follow:

$$A_{region,Z} = \frac{P_{GloCur}}{P_{GloFut}} \times \frac{I_{Glo}}{I_{Reg}}$$

The descriptive explanation can be referred to **Table 3**. The P_{GloCur} and P_{GloFut} respectively represent the current and future (year 2050) global populations, the I_{Glo} and I_{Reg} respectively represent the global and regional average per capita impact in a given impact category.

Accordingly, when Sandin et al. developed the Sandin's procedure, they took the fact that it is unrealistic for anyone to reduce the environmental impact of a product in according to the reduction target within 1 year, and that it would take longer period of time. Therefore, they took the change in population during the period (from the starting point to the end goal) into account.

For this case-study, the year 2050 was chosen as the time horizon, same as in Sandin et al. (2015), because the suggested time gap could provide enough opportunity for "*the development and subsequent market introduction, growth and saturation of new technologies (Grübler,* *2003)…* [and for] *the development and large-scale diffusion of impact-reduction interventions suggested today (Roos et al., 2015)*" (Sandin et al., 2015, p.1687)

3.3.3.1 Data collection

Table 5 lists all the collected data used to develop the allocation factors for three geographies (the United States, China, and the Netherlands) in all perspectives and ethical principles.

Regarding the data sources, all data related to the current and future population were collected from the United Nation (United Nations, 2017). As for the global and regional average per capita impact for each impact category, the data was collected from the suggested source in Sandin et al.'s study (2015).

For climate change, there was no necessity to find data on the emission of each region and the global level as the global target for impact reduction is 100%.

For freshwater eutrophication, the impact per capita data was collected from the national phosphorus footprint from Metson et al. (2012), which is "*a metric of the mined phosphorus required to produce the food consumed per capita per year*" (Sandin et al., 2015, p.1691).

For freshwater use, Sandin et al. used the data from Mekonnen & Hoekstra (2011b) to develop the allocation factor. However, unlike their study, which used the blue and green water footprint of national consumption, the blue water footprint was used as the impact per capita data instead. The reason was because the control variable for freshwater use proposed in the PB-framework of Steffen et al. (2015) is consumptive blue water use only. It is important to mention that this data is not consistent with the data used to identify the boundary and currently known value for freshwater use in Steffen et al. (2015), and this shall be discussed later in the discussion chapter (Chapter 6, Section 6.3.1).

Table 5: List of quantitative data (and its source) used to calculate the allocation factors ($A_{region, Z}$) for all the ethical principles

List	Data	Source
(Population)		
Global population	7.55 billion	United Nations (2017)
Global population in 2050	9.77 billion	United Nations (2017)
US population in 2017	324.46 million	United Nations (2017)
US population in 2050	389.60 million	United Nations (2017)
CN population in 2017	1.41 billion	United Nations (2017)
CN population in 2050	1.36 billion	United Nations (2017)
NL population in 2017	17.0 million	United Nations (2017)
NL population in 2050	17.5 million	United Nations (2017)
(Impact per capita for freshwater use)		
Global average of blue water footprint	153 m^3/year/capita	Mekanon & Hoekstra (2011b)
US blue water footprint	240 m^3/year/capita	Mekanon & Hoekstra (2011b)
CN blue water footprint	117 m^3/year/capita	Mekanon & Hoekstra (2011b)
NL blue water footprint	128 m^3/year/capita	Mekanon & Hoekstra (2011b)
(Impact per capita for the interferences of phosphorus cycle)		
Global average of phosphorus footprint	2.6 kg P-eq/capita/year	Metson et al. (2012)
US phosphorus footprint	• Low legend: 6.01 kg P-eq/capita/year	Metson et al. (2012)

	• High legend: 7.5 kg P-eq/capita/year	
CN phosphorus footprint	• Low legend: 1.51 kg P-eq/capita/year • High legend: 3.0 kg P-eq/capita/year	Metson et al. (2012)
NL phosphorus footprint	• Low legend: 4.51 kg P-eq/capita/year • High legend: 6.0 kg P-eq/capita/year	Metson et al. (2012)

4. Preliminary results

In this chapter, the preliminary results in Phase 1 are presented. Although these results could not be used to answer the research question, they were the information that had been congregated during this study, in order to conduct LCA of the cotton T-shirts – the final results in Phase 1 (see Chapter 5). The preliminary results included (1) the summary of LCA literature review of cotton products, and (2) the life cycle inventory of the cotton T-shirts.

4.1 Literature review summary

Because cotton is a major textile material that poses strong environmental risks, there have been multiple life-cycle studies on the environmental impacts of cotton products, much more than some other fibers in comparison. Therefore, in order to properly conduct the LCA for the cotton T-shirt, it is important to study the existing LCA studies on cotton product first.

Table 6 & **Table 7** (next page) show the summary of 10 LCA literature of cotton products, which were chosen out of all the papers because they were most relevant to the LCA context in this thesis. These studies generally covered the fiber production and fabric manufacturing process which were located in similar countries – i.e. the United States, China, India, and Turkey. Additionally, some of them also assessed the impact in the use and disposal phase as well, however, the studied geographical scopes were either in Europe or in an average-global scale.

The literatures were taken from publicly available sources, and all of them have (at least) 100% cotton product as their studied product(s). Accordingly, the majority of the literature were academic paper or reports conducted by researchers, international non-profit institutions, or consulting companies. There was only one paper that came from the private sector, which was Levi's lifecycle assessment report of its jean product.

Regarding the data collection the literatures, not all of them collected their data using primary sources (e.g. interview and questionnaire), and even if they were, the primary data was collected only in some processes. On the contrary, all of them utilized publicly available literatures and software database, particularly Ecoinvent and Gabi, to either support or primarily use as the data source.

To summarize the findings, the studies altogether concluded that cotton products had significant environmental impacts, particularly global warming potential, water resource depletion, eutrophication, and eco-toxicity impact (Cardoso, 2013; Cotton Incorporated, 2012; Levi Strauss & Co., 2015). They also highlighted three major processes that contributed to the impacts; these were fiber production, fabric manufacturing, and use phase. Cotton fiber production was mostly responsible for the environmental impacts related to water resource and quality due to high amount of freshwater consumption and the use of fertilizer and pesticides (Zhang et al., 2015). Energy or electricity consumption was commonly highlighted as the main factor for global warming potential, especially if the material source were diesel fuel, as it has high environmental impact (Baydar et al., 2015). Since fabric manufacturing often used high amount of energy and electricity, the process consequently represented the main contributor to global warming impact. However, despite the variation of the period length, the use phase was considered the most significant process that contribute to many impact categories (Beton et al., 2014; Levi Strauss & Co., 2015). This was because the process of laundry (and occasionally drying) each time required electricity and detergents, and the longer the period of use the higher the quantity of consumption they would be.

Table 6: Literature review summary (1)

Topic	LCA of cotton and wool	LCA of cotton fiber and fabric	LCA of cotton towel	Environmental improvement potential of textiles	LCA of cotton T-shirt in China
Reference	(Cardoso, 2013)	(Cotton Incorporated, 2012)	(Blackburn & Payne, 2004)	(Beton et al., 2014)	(Zhang et al., 2015)
Location	Tajikistan (fiber production), China (yarn spinning), Italy and China (Dye & bleaching)	Fiber production: the United States, China, & India Fabric manufacturing: Turkey, India, China, and Latin America	The United States	EU-27 countries	China
Functional unit	1 kg of ginned fiber, yarn, dyed and bleached fabric	1000 kg for fibers 1000 kg for knitted fabric	100% dyed cotton tower (600 g)	All type of apparels consumed (the scale is too large to describe here)	100% cotton T-shirt (0.153 kg)
Product system	Fiber production & Fabric manufacturing	Fiber production & Fabric manufacturing	Fiber production, Fabric manufacturing, Use, & Disposal	Fiber production, fabric manufacturing, use, and end-of-life	Fiber production, fabric manufacturing, use, & disposal
Source for the life cycle inventory	• Questionnaire to Hugo Boss's suppliers (primary) • Ecoinvent (secondary)	• Interview and survey (primary) • Literature, national statistics and Gabi's database (secondary)	Literature and other secondary sources	• Literature, database, or technical studies (BIO intelligence service) • Ecoinvent 2.0 database	• Onsite investigation, questionnaire and interview (Primary) • Literature, online database, and Ecoinvent 2.2 (Secondary)
Impact assessment method and categories	Climate change (IPCC2007), Ozone depletion (WMO 1999), Human toxicity (carcinogenic) (USEtox), Acidification (Seppala et al. 2006 and Posch et al. 2008), Freshwater eutrophication (ReCiPe 1.05), Marine eutrophication (ReCiPe 1.05), Freshwater ecotoxicity (USEtox), Water resource depletion (Swiss ecoscarcity 2006)	Acidification potential, Eutrophication potential, Global warming potential, Ozone depletion potential, Photochemical zone creation potential, Primary energy demand, Water Used (gross volume), Water consumed (Net volume), Ecotoxicity potential, Human toxicity potential	Energy consumption, water use, and chemical consumption	All impact category available in ReCiPe both at midpoints and endpoints	CML 2001 & USEtox: Abiotic depletion, Acidification potential, Global warming potential, Photochemical ozone creation potential, Eutrophication potential, Water use, Human toxicity (cancer and non-cancer), Ecotoxicity potential (USEtox)
Exclusion	Carbon equivalent uptake (biogenic carbon), The production and use of natural pesticides, Transportation of fertilizers and pesticides	Human Labor, Construction of capital equipment, Maintenance and operation of support equipment, Production & transport of packaging materials	(Not available)	Hand washing and dry cleaning	Human labor, Construction of capital equipment, Maintenance and operation of support equipment
Conclusion	Fertilizers, irrigation (fiber production); energy consumption , water and wastewater (fabric manufacturing) are the most contributing factors	• Energy and water use are the significant causes to the overall results • Agriculture has a contribution up to 20% in the final results while in water consumption its contribution are around 80% • Energy use & global warming impact are situated in fabric production	The most important stage in the life cycle of the towel is the consumer stage	The significant contributions to the environmental impacts are due to the production (land, water and fertilizer consumption) and use phases (water, detergents, & energy consumption). Cotton are the main contributor among all the fibers.	Water, fertilizers, and pesticide use in the cotton cultivation, and the energy consumption in the dyeing, making-up, and use processes cover the majority of environmental impacts

Table 7: Literature review summary (2)

Topic	LCA of cotton textile products in turkey	LCA of organic cotton knitted fabrics	LCA benchmarking on different textiles	Environmental analysis of a cotton yarn supply chain	LCA of Levi’s jeans and other products
Reference	(Baydar et al., 2015)	(Murugesh & Selvadass, 2013)	(Van Der Velden et al., 2014)	(Bevilacqua et al., 2014)	(Levi Strauss & Co., 2015)
Location	Turkey	(Not available)	(Not available)	Egypt, China, India, US	Global
Functional unit	1000 items of knitted and dyed T-shirt (total weight of 200 kg), 50 washing cycles at 60C temperature	The dyeing and finishing of 1 ton 2/40’s, 100% organic cotton single jersey RFD fabrics	1 kg of (greige) textile	1 kg of dyed cotton yarn	1 pair of Levi’s 501 jeans
Product system	Fiber production, fabric manufacturing	Dyeing and finishing (padding, drying, packing, & transport)	Fiber production, fabric manufacturing, use, & disposal	Fiber production, fabric manufacturing, & use	Fiber production, fabric manufacturing, use & disposal
Source for the life cycle inventory	• Wet processing: primary data given by selected textile planted in Hadimkoy, Istanbul (primary) • Cultivation, ginning, and knitting: literature (secondary)	Primary data collection (but no description on how and where it was collected)	all available data from the public domain (scientific literature and company information), from (LCA) databases, from the emission registration database of the Dutch government, and by contacting companies and experts	Chemical & mechanical treatments in fiber production: Questionnaires sent to suppliers (Primary) Cotton cultivation: reports, national database, Ecoinvent v2 (Secondary)	Company’s internal data
Impact assessment method and categories	Global warming potential (IPCC), Acidification potential (RAINS; computer model), Terrestrial eutrophication potential (RAINS), Aquatic eutrophication potential (RAINS), Photochemical ozone formation potential (EDIP 2003)	Carcinogens, Non-carcinogens, Respiratory inorganics, Ionizing radiation, Ozone depletion, Respiratory organics, Aquatic toxicity, Terrestrial ecotoxicity, Terrestrial acidification, Land occupation, Aquatic acidification, Aquatic eutrophication, Global warming, Non-renewable energy, Mineral extraction	Global warming potential (IPCC2007, 100 years), Acidification potential (ReCiPe), Aquatic eutrophication potential (ReCiPe), Terrestrial eutrophication potential (ReCiPe), Ecotoxicity (USEtox), Fine dust (IMPACT 2002+), Photochemical oxidant formation (ReCiPe) [The result is shown in Eco-cost 2012]	All category in Ecoindicator 99, and global warming potential (IPCC 2007)	Climate change, Water use, Water consumption, Eutrophication, Land occupation, Abiotic depletion (The characterization method is not available)
Exclusion	Softening, drying, ironing in Use phase	The life cycle part of the processing machines is not taken into consideration	Sewing and assembling, distribution, marketing, and sales of the textile	Any impact of less than 5% of the final value is excluded for reasons of numerical strength and agility in gathering data	(Not available)
Conclusion	• Diesel fuel consumption by agricultural machinery is responsible for many environmental impacts • Electric power consumption is another prominent contributor to global warming potential along with other impact categories	Dyeing is the main contributing process in all impact categories. The color ‘T-Blue’ has the highest impact, while ‘Red has the least.	The energy consumption per kilogram yarn is inversely proportional to the yarn size in decitex (i.e., the energy consumption per kilogram is proportional to the length)	The most critical phases of yarn production are Dyeing and Spinning (respectively). The impact of dyeing process is essentially connected to reactive reagents and pigments, electrical and thermal energy, while the impact of Spinning process is due to the demand for electricity.	• Fiber production, predominantly cotton, contributes by a wide margin to water consumption • Consumer care and fabric manufacturing are the most significant phases for climate change impact and energy

4.2 Lifecycle inventory of the cotton T-shirt

In this section, the inventory data of the two cotton T-shirt's life cycle is described. It should be noted that the data is displayed as 1 kg of cotton T-shirts. However, in Section 5.1, the result of the life-cycle impact assessment (LCIA) is shown in a unit of 1 piece of cotton T-shirt (0.21 kg).

4.2.1 Fiber production

As mentioned earlier, the case-study of this thesis was two cotton T-shirts in which the cotton fiber was produced from two different countries: China and the United States. Thus, in some processes, specifically the fiber production and fabric manufacturing (fiber procurement), the development of the inventory had to be divided into two scenarios.

4.2.1.1 Production in China

For fiber production in China, the inventory of ginned cotton fiber, cultivated at farm in China from Ecoinvent database was used. Although there was an LCA study that provided an updated inventory data from primary data gathering (Bevilacqua et al., 2014), the data was taken from the best farms. Therefore, it could not be incorporated to give a better reflection of the average fiber produce processes in China.

Ecoinvent process: “Cotton fibre {CN} | cotton production | Alloc Def, U” (version 3.0.4.0)

4.2.1.2 Production in the United States

Same as the production in China, the inventory from Ecoinvent database was used. Accordingly, Bevilacqua et al. (2014) also provided the updated inventory data from the best farms, but it was not suitable to be incorporated into this study (for the same reason as above)

Ecoinvent process: “Cotton fibre {US} | cotton production | Alloc Def, U” (version 3.0.3.0)

4.2.2 Fabric manufacturing

In fabric production, the inventory of knitted cotton-fabric manufacturing from Ecoinvent, which covered activities from yarn spinning, knitting, batched-dyeing, and making of fabric, was used as the main inventory data. However, since the inventory was for global-average, it did not accurately reflect the context of China. To solve this, an inventory from a recent LCA study on cotton T-shirts in China by Zhang et al. (2015) was used for modification. Additionally, the data of waste water and fiber/fabric loss from the literature was also added to the inventory. **Table 8** lists the inventory data of fabric manufacturing from Zhang et al. (2015) that was used to modify the main inventory data in Ecoinvent. Furthermore, the logistic process of transporting cotton fibers from the source to the manufacturing site was also part of the inventory, as resource procurement should be part of manufacturer's responsibility.

In this phase, the main difference in the inventory of the cotton T-shirt with fiber produced in the United States (US) and China (CN) was the elementary flow of the fiber procurement. For cotton fibers in US, the fiber were assumed to be produced in Missouri – one of main production area of the country (Bevilacqua et al. 2014) – which were then transported by a lorry to a nearby port where they are shipped oversea by a freight to Shanghai port, and later to the manufacturing site in Jiangsu (Zhang et al., 2015). As for the cotton fibers in CN, they were assumed to be produced in Xin Jiang province, a well-known region for cotton farming (Zhang et al., 2015), and were transported by a lorry to manufacturing site in Jiangsu. The distance for each transportation process were calculated using online source (SeaRates LP, n.d.-b)

Ecoinvent processes:

- "Textile, knit cotton {GLO}| textile production, knit cotton, batch dyed | Alloc Def, U" (version 3.0.2.0)
- (US) "Transport, freight, lorry 16-32 metric tons, EURO5 {RER}" (version 3.0.4.0)
- (US) "Transport, freight, sea, transoceanic ship {GLO}" (version 3.0.90.0)

Table 8: Inventory data of cotton fabric manufacturing in China from Zhang et al. (2015) (1 kg of cotton T-shirt)

Material/Process input	Quantity	Unit	Location	Source
Tap water	185.62	kg	GLO	Zhang et al. 2015
Cotton fiber	1.54	kg	CN	Zhang et al. 2015
Electricity (low voltage)	12.95	kWh	CN	Zhang et al. 2015
Kraft paper (bleached)	0.020	kg	GLO	Zhang et al. 2015
Lorry transport (7.5-16 ton)	3800	km	RER	Zhang et al. 2015

Emission to water	Quantity	Unit	Location	Source for the quantity
Wastewater	84.30	kg	-	Zhang et al. 2015

Waste outputs	Quantity	Unit	Location	Source of the quantity
Waste textile (fiber loss)	0.54	kg	-	Zhang et al. 2015

Table 9: Inventory data of fiber procurement from the United States (1 kg of cotton T-shirt)]

Material/Process input	Quantity	Unit	Location	Source
Lorry transport (16-32 ton)	1029	km	RER	Bevilacqua et al., 2014; SeaRates LP (n.d.-a)
Freight transport	22554	km	GLO	SeaRates LP (n.d.-a)

Table 10: Inventory data of fiber procurement from China (1 kg of cotton T-shirt)

Material/Process input	Quantity	Unit	Location	Source
Lorry transport (7.5-16 ton)	3800	km	RER	Zhang et al. 2015

4.2.3 Distribution

After the T-shirts were made and put into a packaging, the product were assumed to be shipped to the Netherland by a transoceanic ship, from Shanghai to Rotterdam port. Again, the distance for the shipping route was estimated by the same online source (SeaRates LP, n.d.-b).

Ecoinvent processes:

- "Transport, freight, sea, transoceanic ship {GLO}" (version 3.0.90.0)

Table 11: Inventory data of 1 kg of cotton T-shirt distribution from China to the Netherlands

Process input	Quantity	Unit	Location	Source
Freight transport	19360	km	GLO	SeaRates LP (n.d.-b)

4.2.4 Consumer use

In the use phase, cloth washing and tumble drying were highlighted as the main activities. The reason was because both activities consumed high amount of water and electricity (see literature review). The use period of the T-shirt was assumed to be 1 year, and within that period, the product was assumed to be washed 50 times. In addition, according to Beton et al. (2014), the majority of European consumers occasionally used tumble dryer to dry their clothes – which was about 25% of the total washing cycles (12 times).

4.2.4.1 Washing

Unlike developing countries, almost every household in Europe, including the Netherlands, washed clothes using washing machine for convenience and time-saving (Steinberger, Friot, Jolliet, & Erkman, 2009; Zhang et al., 2015). As a result, electricity was another important input in the process (besides water). The amount of electricity and water consumption were determined based on the efficiency of the machine, and since the average life expectancy of white-goods is about or over 10 years (Debell & Dardis, 1979), the current washing machine in many households was, therefore, assumed to be bought in 2008. Accordingly, the average energy consumption of washing machine sales in Europe in that year was 1.02 kWh/cycle, while the water consumption was 50.45 liter/cycle (Michel, Attali, Bush, & Topten, 2016). In term of washing behavior, several studies indicate that the average load that the European households wash clothes each time is 3.7 kg (Pakula & Stamminger, 2013; Stamminger & Schmitz, 2013). By combining the washing machine efficiency and the use behavior, the total electricity consumption used to wash the product throughout its lifetime was calculated.

Another input which had high influence to the impact assessment in cloth laundry was the consumption of washing detergents. Here, the inventory of the product suggested by Beton et al. (2014), who adopted the original inventory from Saouter and van Hoof (2002), was used as reference. The reason for using the suggested inventory instead of the original one was because Beton et al. adjusted the inventory in order to match with the available data in Ecoinvent. Additionally, the average dosage per wash cycle was assumed to be about 0.122 kg (Saouter and van Hoof, 2002)

Table 12: Inventory data for washing 1 kg of cotton T-shirt throughout one year (0.122 kg of detergents per wash cycle; 50 wash cycles)

Material/process input	Quantity	Unit	Location	Source
Electricity (low voltage)	13.76	kWh	NL	Mitchel et al. (2016)
Tap water	681.81	kg	RER	Mitchel et al. (2016)
Ethoxylated alcohols (AE11)	0.035	kg	RER	Beton et al. (2014)

Ethoxylated alcohols (AE7)	0.071	kg	RER	Beton et al. (2014)
Alkylbenzene sulfonate	0.14	kg	RER	Beton et al. (2014)
Acetic acid	0.091	kg	RER	Beton et al. (2014)
Layered sodium silicate	0.053	kg	RER	Beton et al. (2014)
Zeolite	0.35	kg	RER	Beton et al. (2014)
Sodium percarbonate	0.30	kg	RER	Beton et al. (2014)
Sodium, perborate	0.15	kg	RER	Beton et al. (2014)
Sodium, perborate	0.20	kg	RER	Beton et al. (2014)
Sodium sulphate	0.007	kg	RER	Beton et al. (2014)
Water (completely softened)	0.25	kg	RER	Beton et al. (2014)
Paper	0.36	kg	RER	Beton et al. (2014)
Corrugated board	1.78	kg	RER	Beton et al. (2014)
Polyethylene	0.13	kg	RER	Beton et al. (2014)

Emission	**Quantity**	**Unit**	**Location**	**Source**
BOD5	0.11	kg	EU	Beton et al. (2014)
COD	0.26	kg	EU	Beton et al. (2014)
Total Phosphorus	0.00000076	kg	EU	Beton et al. (2014)
Total Nitrogen	0.0000015	kg	EU	Beton et al. (2014)
Detergent oil	0.000012	kg	EU	Beton et al. (2014)
Ammonia	0.000000089	kg	EU	Beton et al. (2014)
Metals (unspecified)	0.18	kg	EU	Beton et al. (2014)

Output to technosphere	**Quantity**	**Unit**	**Location**	**Source**
Wastewater	0.68	kg	RoW	Beton et al. (2014)

4.2.4.2 Drying

The main input in drying process was electricity consumption. The average electricity consumption of European tumble dryer sales in 2008-2010 was 3.5 kWh/cycle (Michel et al., 2016). The load of cloth was assumed to be the same as the load put in washing machine (3.7kg). However, the frequency of T-shirt drying by tumble dryer was only 25% of the washing behavior, which was about 12 times in one year (Beton et al., 2014). Therefore, the total electricity consumption for drying 1 kg of cotton T-shirt through its use period was 11.82 kWh.

Table 13: Inventory data for drying 1 kg of cotton T-shirt through a year (12 cycles)

Material/process input	**Quantity**	**Unit**	**Location**	**Source**
Electricity (low voltage)	11.87	kWh	NL	Mitchel et al. (2016)

4.2.5 Disposal

Before the inventory for disposal phase could be developed, the information on textile waste treatment in the Netherlands from the Dutch Waste Management Association (2013) was used to define the context. According to the organization, each year the Netherlands disposes about 240 kilotons of used clothing and textiles; 71% of this is discarded through incineration (with energy recovery); 19% is collected for reused (second-hand products); while the rest 10% is downcycled as other products (e.g. wiping clothes, insulations). To confirm the information, the numbers were crosschecked with the latest research on Dutch clothing consumption, conducted by Hogeschool van Amsterdam and its associates (Maldini et al., 2017), and the result showed similar proportion.

In this thesis, the downcycling process of textile wastes was excluded from system-boundary as there were multiple options in which the wastes can be downcycled; the inventory would be too complex if it were to include the process into account, despite its small amount of share. Therefore, the inventory for the disposal only included the wastes that undergone incineration and re-collection for reuse purpose. The result of reusing the products again was considered as the avoided impact from incinerating the product for energy.

For the inventory of textile waste incineration (with energy recovery), the inventory of textile waste treatment by municipal incineration in Ecoinvent database was used as the background inventory. Since the waste was incinerated with energy recovery, the inventory was modified by adding the energy outputs in the form of electricity and heat. These outputs from the techno-sphere were considered as the avoided impacts. Their values were calculated by multiplying the value of each products when burning 1 GJ of household wastes (in Dutch context) with the heating value of 0.21 kg of cotton waste (Nielsen, n.d.).

Table 14: Inventory data of incinerating a cotton T-shirt (with energy recovery)

Output (avoided impacts)	Quantity	Unit	Location	Source
Electricity (high voltage)	0.34	MJ	NL	Nielsen, n.d.
Heat (natural gas)	0.73	MJ	RER	Nielsen, n.d.

5. Final results and interpretation

5.1 Impact assessment result and significant issues identification

Figure 11-13 (below) show the impact assessment throughout the lifecycle of two cotton T-shirts. These impacts were shown the scale of the functional unit – that was one piece of cotton T-shirt (0.21 kg).

As can be seen, the environmental impact was assessed based on three impact categories: (1) Global warming potential, (2) Freshwater eutrophication, and (3) Freshwater consumption. For the sake of the clarity, the cotton T-shirt of which the fibers were produced in the United States would be called “T-shirt US-CN-NL”. Correspondingly, the T-shirt of which the fibers were produced in China would be called “T-shirt CN-NL”.

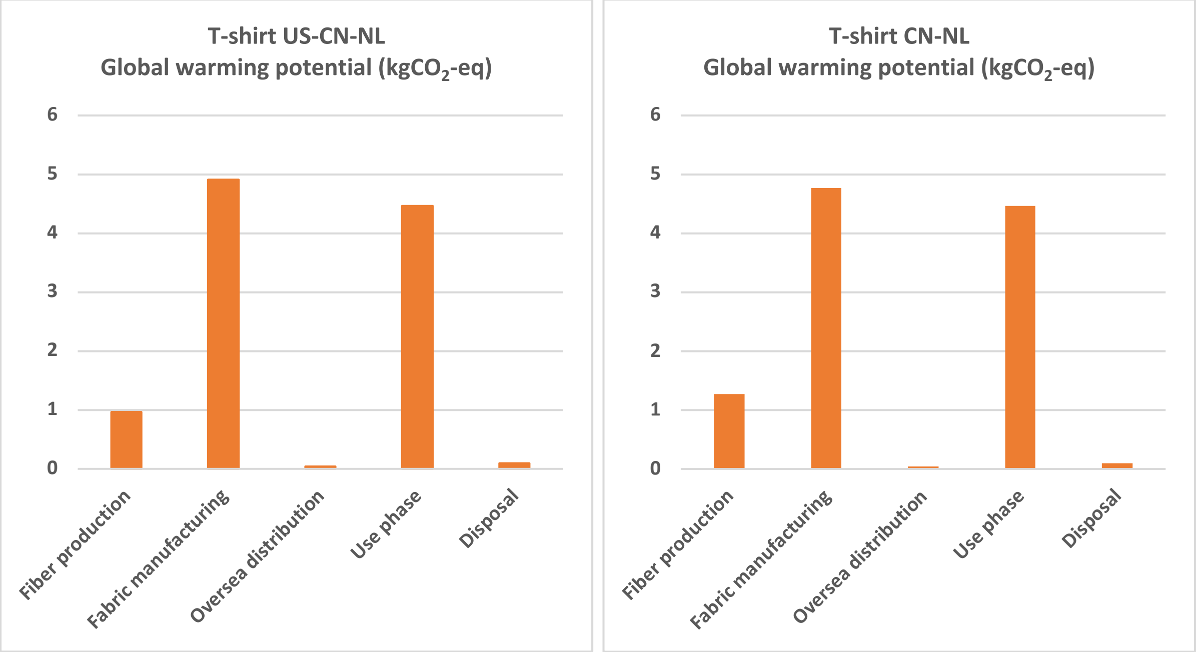


Figure 11: LCIA of cotton T-shirt for global warming potential in Scenario US-CN-NL (left) and Scenario CN-NL (right)

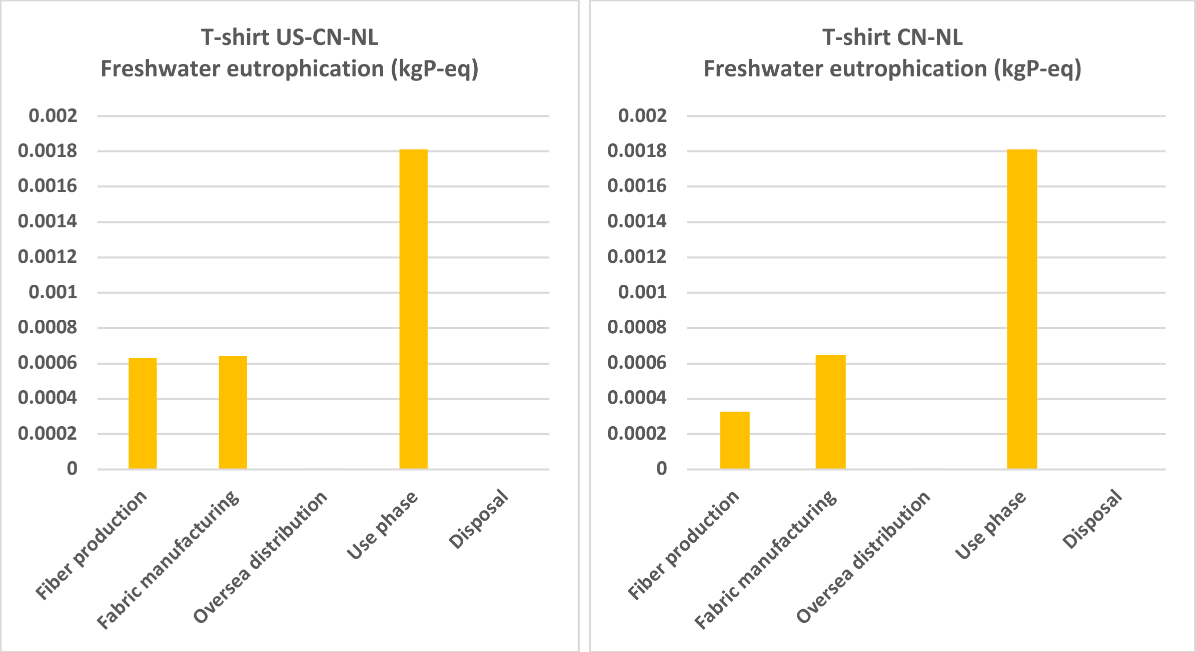


Figure 12: LCIA of cotton T-shirt for freshwater eutrophication in Scenario US-CN-NL (left) and Scenario CN-NL (right)

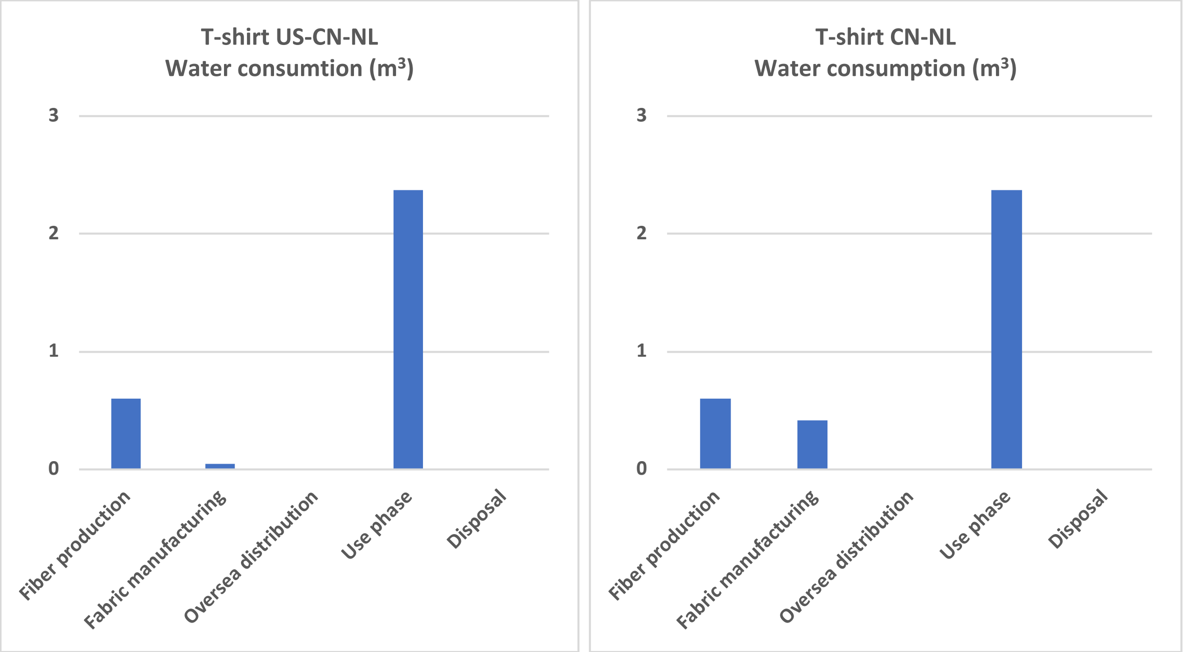


Figure 13: LCIA of cotton T-shirt for water resource depletion in Scenario US-CN-NL (left) and Scenario CN-NL (right)

From the outlook, there were three main phases that significantly contribute to the environmental impacts of both cotton T-shirts – these were fiber production, fabric manufacturing, and use phase. The fiber production had an impact on all three categories in certain degree, while the manufacturing of T-shirt particularly had a strong impact on global warming potential. However, the impact of the products in all three categories was dominated by the use phase in the end. As for the oversea distribution and disposal phase, the impacts from the two phases were negligible, if none at all.

The significant processes that contribute to the environmental impacts in each life-cycle phase of both cotton T-shirts is described in following sub-sections. The quantitative numbers of the impacts are described in the unit of 1 piece of T-shirt (0.21 kg)

5.1.1 Fiber production

In fiber production, the United States (US) and China (CN) had somewhat an equal amount of global warming impact (0.97 and 1.27 kgCO_2 respectively). The two countries also shared the same major cause of impact as well – that was the electricity production from hard coal and lignite (28-36%). The water consumption result also showed the same pattern both in the quantity and cause of the impact. However, the fiber production in US had twice the impact on freshwater eutrophication. This was mainly because the subprocess of the electricity consumption in US cotton production requires more treatment of hard coal spoils.

Table 15: The significant processes contributing to the environmental impacts in the fiber production in the United States (unit: 1 piece of T-shirt)

Impact category	Impact assessment	Significant processes
Global warming potential	0.97 kg CO_2-eq	• Electricity production from lignite and hard coal (28.6%) • Direct emission of greenhouse gases (22.8%) - particularly carbon dioxide and dinitrogen monoxide • Nitric acid manufacturing (9.2%)
Freshwater eutrophication	0.00063 kg P-eq	• Treatment of hard coal spoils (55.7%) • Direct emission of phosphorus and phosphate to water (18.8%)
Water consumption	0.603 m^3	• Irrigation (99%)

Table 16: The significant processes contributing to the environmental impacts in the fiber production in China (unit: 1 piece of T-shirt)

Impact category	Impact assessment	Significant processes
Global warming potential	1.27 kg CO_2-eq	• Electricity production from hard coal (36.2%) • Direct emission of greenhouse gases (18.5%) - particularly carbon dioxide and dinitrogen monoxide • Hard coal mine operation (17.2%) • Nitric acid manufacturing (7%)
Freshwater eutrophication	0.00033 kg P-eq	• Direct emission of phosphorus and phosphate to water (36.5%) • Treatment of hard coal spoils (32.8%)
Water consumption	0.602 m^3	• Irrigation (99%)

5.1.2 Fabric manufacturing

Contrary to fiber production, the impact of fabric manufacturing mostly involved with global warming potential. In fact, the phase caused the highest amount of impact throughout the lifecycle (>40%). The major contributor to the impact came from the consumption of electricity generated by hard coal, and the treatment of hard coal spoils. Contrary to the conclusion in Zhang et al. (2015), the water consumption from fabric manufacturing was considerably low when compared to the fiber production and use phase. Moreover, in the case of CN-NL, most of the water consumption in this phase was dominated by the procurement of the cotton fiber.

This was because the amount of hydropower electricity consumption for operating road maintenance (for lorry to safely run) is much higher.

Table 17: The significant processes contributing to the environmental impacts in fabric manufacturing phase of T-shirt US-CN-NL (unit: 1 piece of T-shirt)

Impact category	Impact assessment	Significant processes
Global warming potential	4.91 kg CO_2-eq	• Electricity production from hard coal (46.4%) • Hard coal mine operation (22.%) • Tetrafluoroethylene production (9.4%)
Freshwater eutrophication	0.00064 kg P-eq	•Treatment of hard coal spoils (73.8%)
Water consumption	0.049 m^3	Consumption of water in the fabric manufacturing process (99%)

Table 18: The significant processes contributing to the environmental impacts in fabric manufacturing phase of T-shirt CN-NL (unit: 1 piece of T-shirt)

Impact category	Impact assessment	Significant processes
Global warming potential	4.77 kg CO_2-eq	• Electricity production from hard coal (46.4%) • Hard coal mine operation (22.%) • Tetrafluoroethylene production (9.4%)
Freshwater eutrophication	0.00065 kg P-eq	•Treatment of hard coal spoils (73.8%)
Water consumption	0.42 m^3	• Hydropower electricity production (a subprocess in lorry transport) (86%)

5.1.3 Oversea distribution

Compare to lorry transport, freight transport via transoceanic ship had much lower impact (despite the longer travel distance). The impact from the oversea distribution was hardly noticeable in all three impact categories. Nevertheless, it was important to note that most of the environmental impact in this phase comes from the consumption of fuel oil, lignite, and hard-coal. In addition, 90% of the freshwater eutrophication were caused by the treatment of lignite and hard-coal used either as a direct fuel or to produce electricity.

Table 19: The significant processes contributing to the environmental impacts in oversea distribution phase (unit: 1 piece of T-shirt)

Impact category	Impact assessment	Significant processes
Global warming potential	0.047 kg CO_2-eq	• Direct emission during freight transport (68%)
Freshwater eutrophication	0.0000061 kg P-eq	• Treatment of lignite and hard-coal spoils (91%)
Water consumption	0.00015 m^3	• Production of heavy fuel oil (34.5%) • Decarbonized water consumption (16%) • Electricity production from hydropower (7.8%)

5.1.4 Product use

Use phase was the most impactful phases in the T-shirt's life cycle. It had the highest impact on freshwater consumption and eutrophication in both LCA scenarios, with the amount of 2.37 m^3 (78%) and 0.00181 kg P-eq (58%) respectively. Three major inputs were repetitively consumed over the year; these were low-voltage electricity, water, and washing detergents. The production of electricity played a significant role in global warming potential and water consumption. In global warming potential, the production of electricity from natural gas, hard coal, and lignite altogether contributed almost 50% of the impact. In water consumption, the electricity generated from hydropower contributed almost 90% of the impact; accordingly, most of the hydropower electricity (70%) was consumed during process of paper and corrugated board manufacturing (detergent's packaging). Surprisingly, the use of tap water was accounted for 7% of the consumption. This indicated that the most of the direct water use (from tap) in the washing process was return back to the natural water catchments. As for the freshwater eutrophication, the impact was mostly caused by the treatment and disposal of spoils (as a result of using electricity production from coal and lignite).

Table 20: The significant processes contributing to the environmental impacts in product use phase (unit: 1 piece of T-shirt)

Impact category	Impact assessment	Significant processes
Global warming potential	4.47 kg CO_2-eq	• Electricity production from natural gas (25%) • Electricity production from hard coal and lignite (23%) • Zeolite powder production (7%)
Freshwater eutrophication	0.0018 kg P-eq	• Treatment and disposal of spoils from coal and lignite mining in surface landfill (55.7%) • Zeolite powder generation (9%)
Water consumption	2.37 m^3	• Electricity generation from hydropower (89%) – mostly used in the process of paper and corrugated board production (detergent's packaging) • Tap water at user (7%)

5.1.5 Disposal

In the disposal phase, the cotton T-shirt was either incinerated with energy recovery at the municipality facility, or is reused. Based on the LCI analysis (Section 4.2), the ratio between the two treatment was assumed to be about 8 to 2. The result of reusing the cotton T-shirt was considered as the avoided impact (negative value) from disposing the T-shirt for incineration. **Table 21** shows the significant processes that caused environmental impact in the incineration process. Although there were certain impacts caused by incinerating textile waste, the recovery of energy also played role as the avoided impact from producing the energy by the conventional methods (e.g. coal, hydropower, & natural gas). Base on the assessment result, the incineration process overall created a slight impact towards global warming. This was mainly caused by the processes of incinerating textile wastes, releasing carbon dioxide to the air. However, in freshwater eutrophication and water consumption, the incineration with energy recovery appeared to create a positive impact to the two categories because the process prevented further risk of freshwater eutrophication and water consumption from other unwanted processes. By recovering the energy from burning textile wastes, the impact from producing high voltage electricity using coal, lignite or hydropower was avoided. This means that the process of disposing coal and lignite spoils, or generating electricity through hydropower, which highly contribute to freshwater eutrophication and water consumption respectively, were also avoided. Therefore, the visible environmental impact from incinerating textile wastes was only global warming potential.

Table 21: The significant processes contributing to the environmental impacts in disposal phase (unit: 1 piece of T-shirt)

Impact category	**Impact assessment**	**Significant processes**	
		Environmental impacts	Avoided environmental impacts from energy recovery
Global warming potential	0.099 kg CO_2-eq	• Textile waste incineration (103.7%) • Liquid ammonia production (2.6%) • Sodium hydroxide production (1.1%)	• High voltage electricity production at grid (-10%) • Heat production from natural gas (-8.5%)
Freshwater eutrophication	-0.0053 kg P-eq	• Sodium hydroxide production (-27%) • Textile waste incineration (-11.5%) • Liquid ammonia production (-11%) • Titanium dioxide (-11%) • Heat production from natural gas (-12%) • Waste cement (-4.2%)	• Heat production from natural gas (-20%) • High voltage electricity production at grid (-174%)
Water consumption	-0.0000022 m^3	• Decarbonize water consumption (-3%) • Liquid ammonia production (-1.4%)	• High voltage electricity production (105%) • Heat production from natural gas (0.25%)

5.2 Impact-reduction target of the cotton T-shirt

In this section, the result of the study in Part 2 is presented, that is the development of the impact reduction targets along the lifecycle of the cotton T-shirt, using Sandin's procedure. **Table 22-24** shows the impact-reduction targets of the product (no matter what process) under different geographical scope: United States, China, and the Netherlands. It should be noted that the targets are expressed in percentages, and, therefore, are not LCA results. In other words, they do not scale with the functional unit.

As already mentioned in Phase 2's methodology (Section 3.3), the cotton T-shirt was considered as a product of luxury with less significant value to human well-being (Perspective B), and that all individuals had the rights to have an equal share of globally allowed-impact target (Principle 1). The impact-reduction targets under the selected allocation methods (Perspective B, Principle 1) were highlighted with green color in each table. Accordingly, the description of the result in this section would specifically focus on the highlighted impact-reduction targets. To start with, the result suggests that the impact of global warming potential for all the three countries "*must be reduced by 100% in term of net impact*" regardless of the geographical scope and market segment (Sandin et al., 2015, p.1687). As for the other two impact categories, the results are very much dependent on the geographical context. In freshwater use, the reduction target of China and the Netherlands are much lower than the United States because they have lower blue water footprint, which is about 22% and 29% respectively – see **Table 5**. Similarly, in freshwater eutrophication, the reduction targets in the United States and the Netherlands are higher than China; the target for the two countries in the selected perspective are over 90%. The reason is because both countries has much higher amount of national footprint in phosphorus cycle in comparison to China, whose footprint is lower than the global average (Metson et al., 2012). As a result, processes within the life-cycle of the cotton T-shirt that occur or belong to the responsibility of China would have the lowest impact-reduction target (except for global warming potential), while those that occur or belong to the United States or the Netherlands would have higher reduction targets.

Table 22: The impact-reduction targets of a cotton T-shirt in the geographical context of the United States, under different allocation approaches and principles

The United States								
Ethical principle			**Principle 1: Individual rights**		**Principle 2: Historical right of sectors**	**Principle 3: Historical populations**	**Principle 4: Historical debt of individual of populations**	
Earth system	LCA related impact categories	Perspective	%		%	%	%	
Climate change	Climate change	A-C	100		100	100	100	
Freshwater use	Water consumption	A	24.14		-28.25	0.90	59.73	
		B	62.07		35.87	50.45	79.86	
		C	-51.71		-156.51	-98.19	19.45	
			Low legend	High legend			Low legend	High legend
Interference with the phosphorus cycle	Freshwater eutrophication	A	85.29	88.21	63.3	71.69	94.7	96.59
		B	92.65	94.11	81.68	85.84	97.35	98.29
		C	70.59	76.43	26.71	43.37	89.4	93.19

Table 23: The impact-reduction targets of a cotton T-shirt in the geographical context of China, under different allocation approaches and principles

China								
Ethical principle			**Principle 1: Individual rights**		**Principle 2: Historical right of sectors**	**Principle 3: Historical populations**	**Principle 4: Historical debt of individual of populations**	
Earth systems	LCA related impact categories	Perspective	%		%	%	%	
Climate change	Climate change	A-C	100		100	100	100	
Freshwater use	Water consumption	A	-55.6		-59.09	-22.92	-110.2	
		B	22.2		20.46	38.54	-5.1	
		C	-211.2		-218.17	-145.84	-320.4	
			Low legend	High legend			Low legend	High legend
Interference with the phosphorus cycle	Freshwater eutrophication	A	41.46	70.54	54.55	64.88	-4.12	73.62
		B	70.73	85.27	77.27	82.44	47.93	86.81
		C	-17.08	41.07	9.09	29.76	-108.24	47.24

Table 24: The impact-reduction targets of a cotton T-shirt in the geographical context of the Netherlands, under different allocation approaches and principles

The Netherlands								
Ethical principle			**Principle 1: Individual rights**		**Principle 2: Historical right of sectors**	**Principle 3: Historical populations**	**Principle 4: Historical debt of individual of populations**	
Earth systems	LCA related impact categories	Perspective	%		%	%	%	
Climate change	Climate change	A-C	100		100	100	100	
Freshwater use	Water consumption	A	-42.23		-49.76	-15.72	-65.33	
		B	28.89		25.12	42.14	17.33	
		C	-184.46		-199.53	-131.43	-230.66	
			Low legend	High legend			Low legend	High legend
Interference with the phosphorus cycle	Freshwater eutrophication	A	80.40	85.27	57.21	66.94	89.01	93.79
		B	90.20	92.63	78.61	83.47	94.50	96.89
		C	60.80	70.54	14.42	33.88	78.02	87.58

5.3 Result interpretation

Based on the two results, several implications can be made in term of environmental impact management along the value chain of the cotton T-shirts. This section will describe and summarize those implications. However, the practicality and limitation of the result, which is obviously plenty, would be discussed in the discussion chapter (see Section 6.2, Chapter 6).

Figure 14-16 (below) show the comparison between the original environmental impacts of the two cotton T-shirts along their lifecycles and the environmental impacts they are allowed to cause in order to respect the PB. The gap between the two quantities represents how much the impacts need to be reduced.

To begin with, the result suggests a drastic reduction of the overall impacts throughout the lifecycle of both products in all impact categories, particularly the climate change (global warming potential), as all the current impact has to be reduced to in term of *net impact*, regardless of geographical scope and market segment. This means that after balancing all the release and offset of greenhouse gases (GHG), the net GHG emission in each phase of the products' lifecycle must be equal to zero. Since fiber manufacturing and use phase both have significant impact in the category, the technological and behavioral aspect should be the focus in GHG mitigation strategy. Furthermore, as it is realistically impossible to achieve zero net emission through mitigation of GHG emission only, offset programs and Carbon credit should also be considered in parallel.

In water consumption, there is a gap between the impact-reduction targets of the three countries, whereas China and the Netherlands have an exceptionally low targets (22-29%) in comparison to the United States (62%). This gap indicates two possible suggestions for value chain managers. First, China has an advantageous position to be the suppliers than the United States because it has higher ceiling for impact appropriation; particularly in fiber production where the LCIA result shows an equal amount of water consumption for the production in both countries. Secondly, in the case of T-shirt US-CN-NL, it is more urgent to mitigate the impact in fiber production than the use phase, despite its higher amount of consumption, due to higher reduction target.

In freshwater eutrophication, all three countries have high impact-reduction targets. Thus, the amount of impact reduction are significant throughout the lifecycle of both products. However, unlike climate change, the targets are not expressed in term of net value, so the impact cannot be offset. This is very challenging for value chain managers as phosphorus related compounds are necessarily used in all phases of the products – either as direct and indirect inputs.

To summarize, the result of the study indicates potential applications for clothing companies to use the result to strategize impact reduction strategy along the value chain of their business, for example, to prioritize the environmental impact of a product, and to evaluate locations for business activities (targeting area with lower impact-reduction targets). Though, the result is not recommend to be used to set a quantitative goal in impact-reduction, as the targets are impractical in term of number and science (this would be later discuss in Chapter 6, Section 6.3). However, before the concept can be used in real practice, there are multiple limitations and challenges in the studies, both in the LCA and in Sandin's procedure, which jeopardizes the accuracy and the practicality of the application. These issues are going to be discussed in the next chapter, in order to address future recommendations.

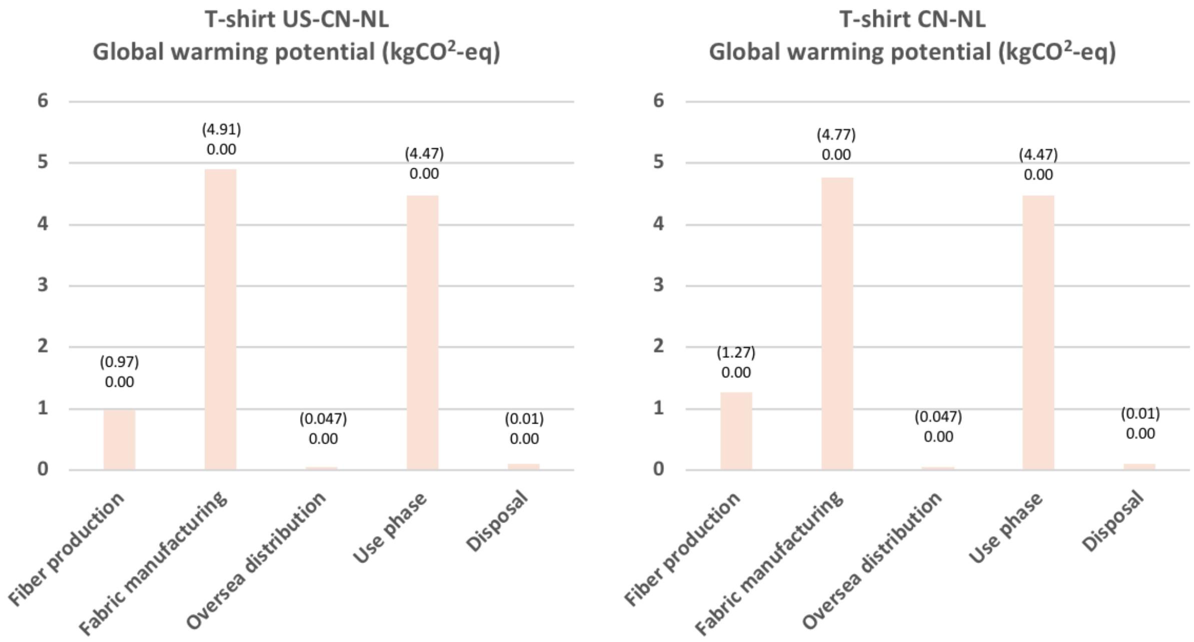


Figure 14: The comparison between the original global warming potential impact of the cotton T-shirt in each phase versus the impact after being reduced in according to the impact-reduction targets. The numbers with bracket represents the original impact.

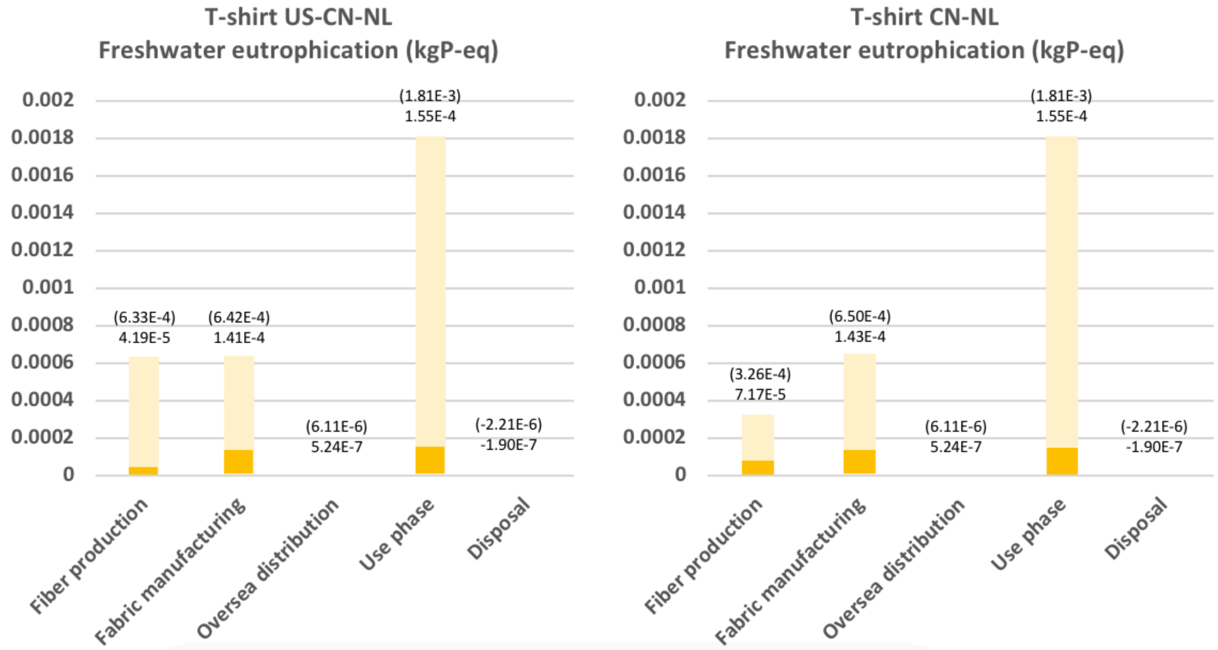


Figure 15: The comparison between the original freshwater eutrophication impact of the cotton T-shirt in each phase versus the impact after being reduced in according to the impact-reduction targets. The numbers with bracket represents the original impact.

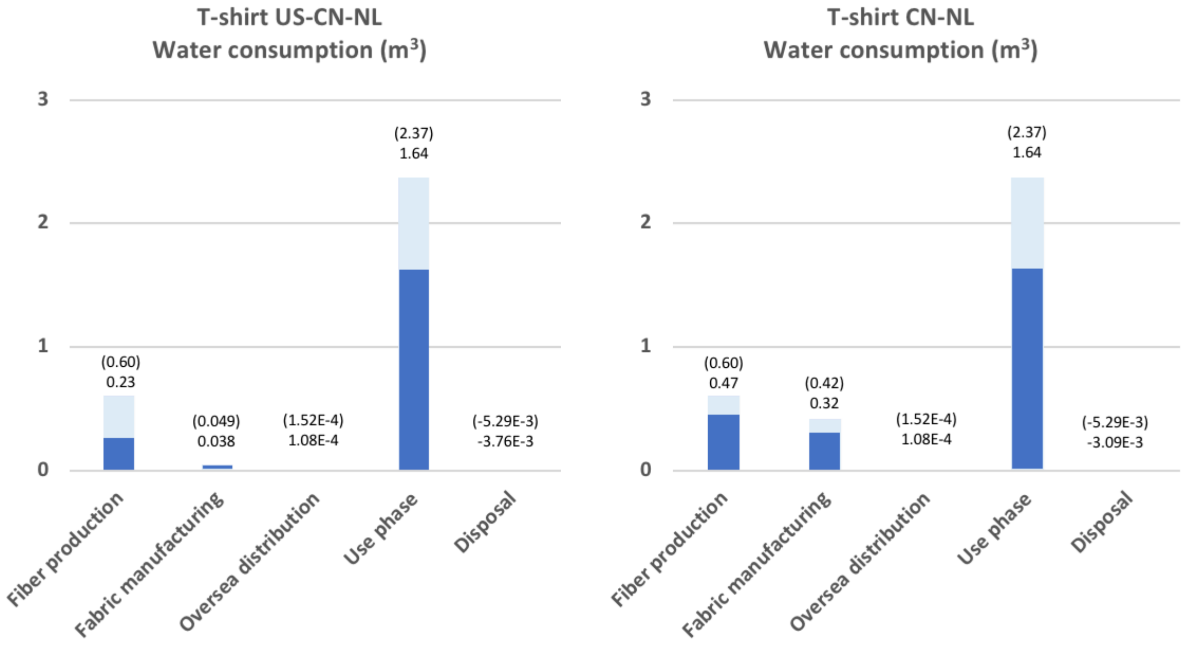


Figure 16: The comparison between the original water consumption impact of the cotton T-shirt in each phase versus the impact after being reduced in according to the impact-reduction targets. The numbers with bracket represents the original impact.

6. Discussion

The purpose of this chapter is to discuss the limitations and challenges of this research and its findings, in order to provide future recommendations. The discussion is divided into three main topics. The first discussion topic is about (1) the LCI issues of the case-study: the quality, sensitivity and uncertainty of data used. After that, the discussion would proceed to the second and third topic which are related to this thesis's second objective – (2) the practicality for textile companies to reduce the environmental impact according to the impact-reduction target, and (3) the limitations of applying Sandin et al's impact-reduction target development procedure from the PB-framework to LCA context of a product.

6.1 LCI data quality, sensitivity and uncertainty check

6.1.1 Data quality improvement

Regarding the data quality, the inventory data for fiber production of the two products need to be updated. As already mentioned in Section 4.2, the inventory from Ecoinvent database version 3 was used (without any modification). Accordingly, there were two main issues with choice of selection. First of all, unlike Ecoinvent version 2, version 3 has less transparent methodology; less information about the numbers and assumptions was disclosed (even they are more up to date). Secondly, the numbers in the inventory of cotton fiber production in the United States and China were almost exactly the same, only the geographical context was different – i.e. the electricity input based on the technologies used in each country. This explains why the LCA results of fiber production in the United States and China were similar in some impact categories. For this LCA study, there was no literature that provides such primary data found in the literature review. Thus, in order to improve the accuracy of the assessment, primary data for the average fiber production of both country is recommended to be used when constructing the inventory of the process.

6.1.2 Sensitivity analysis

Based on the impact assessment result, the most significant process that majorly affected the environmental impacts throughout the life-cycle was the consumption of electricity (see Section 5.1). Depending on the source of electricity production, the process can influence different impact categories. For example, electricity production from hard coal or lignite can cause impact to climate change due to raw material production; it could also cause freshwater eutrophication due to the sub-process of lignite and coal spoil treatment/disposal. If the electricity were generated by hydropower, it would then has impact on water consumption due to water evaporation (Mekonnen & Hoekstra, 2012). Thus, practitioners must ensure that the inventory on the amount and characteristics of electricity consumption, including its source of production, are collected with accurate representation of the context, as it can significantly influence the LCA result.

To elaborate the above argument further, a LCA of cotton T-shirt was conducted again to show how sensitive the technology for electricity production was to the result. This time, all the direct electricity inputs throughout the product-system (excluding the electricity used in the subprocesses) were assumed to be generated from renewable sources. The aim was to elaborate how the source of electricity production could influence the impact assessment result, and to show the potential impact reduction from using renewable energy sources. To do this, all the direct electricity inputs in each process of the existing LCI were replaced with electricity generated from photovoltaic (PV) system. Below were the processes from Ecoinvent database chosen as the replacements in each phase of life-cycle:

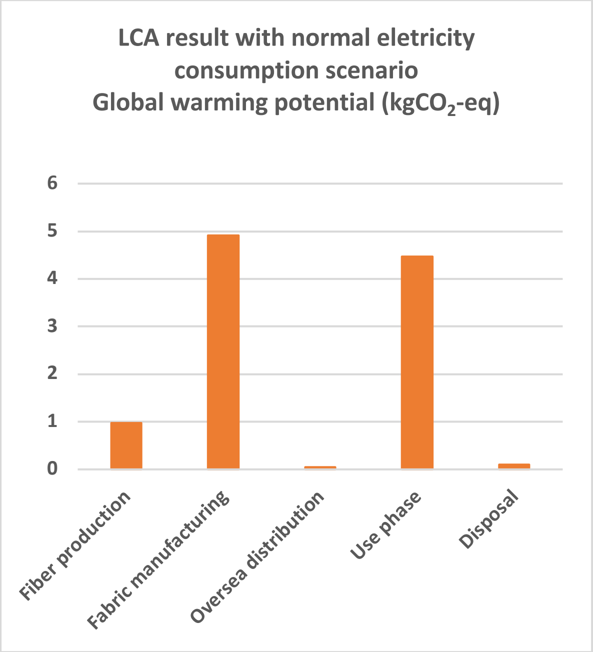
Fiber production (US): “Electricity, low voltage {WECC, US only} | electricity production, photovoltaic, 570kWp open ground installation, multi-Si | Alloc Def, U”

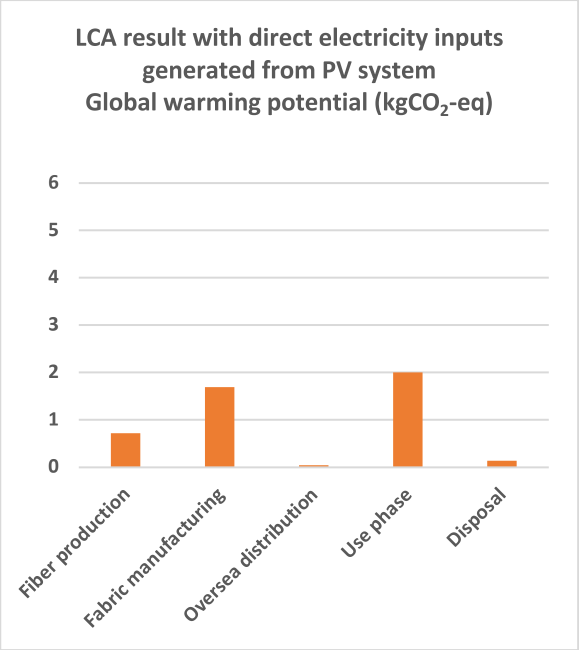
Fabric manufacturing (CN): “Electricity, low voltage {CN-JS} | electricity production, photovoltaic, 570kWp open ground installation, multi-Si | Alloc Def, U”

Product use (NL): “Electricity, low voltage {NL} | electricity production, photovoltaic, 570kWp open ground installation, multi-Si | Alloc Def, U”

Disposal: No replacement (the energy inputs were all heat energy, not electricity)

The result of the assessment is shown in **Figure 17** (3 figures combined). Accordingly, it shows that the replacements of current direct electricity inputs with electricity produced from renewable sources, in this case photovoltaic (PV) system, significantly reduced the product’s impact on global warming potential and freshwater eutrophication. The reason is because the process of electricity production from hard coal, which was the main cause of both impact in many lifecycle phases, was replaced. However, the change did not have significant effect on water consumption throughout the lifecycle, since there was no electricity from hydropower used in that phase (e.g. fiber production and fabric manufacturing), or even if there were, it was not used as direct inputs – for example, most of the hydropower electricity consumed in the use phase came from the electricity used to produce paper-wood and corrugated board in detergent packaging, not the washing machine, nor the tumble dryer.





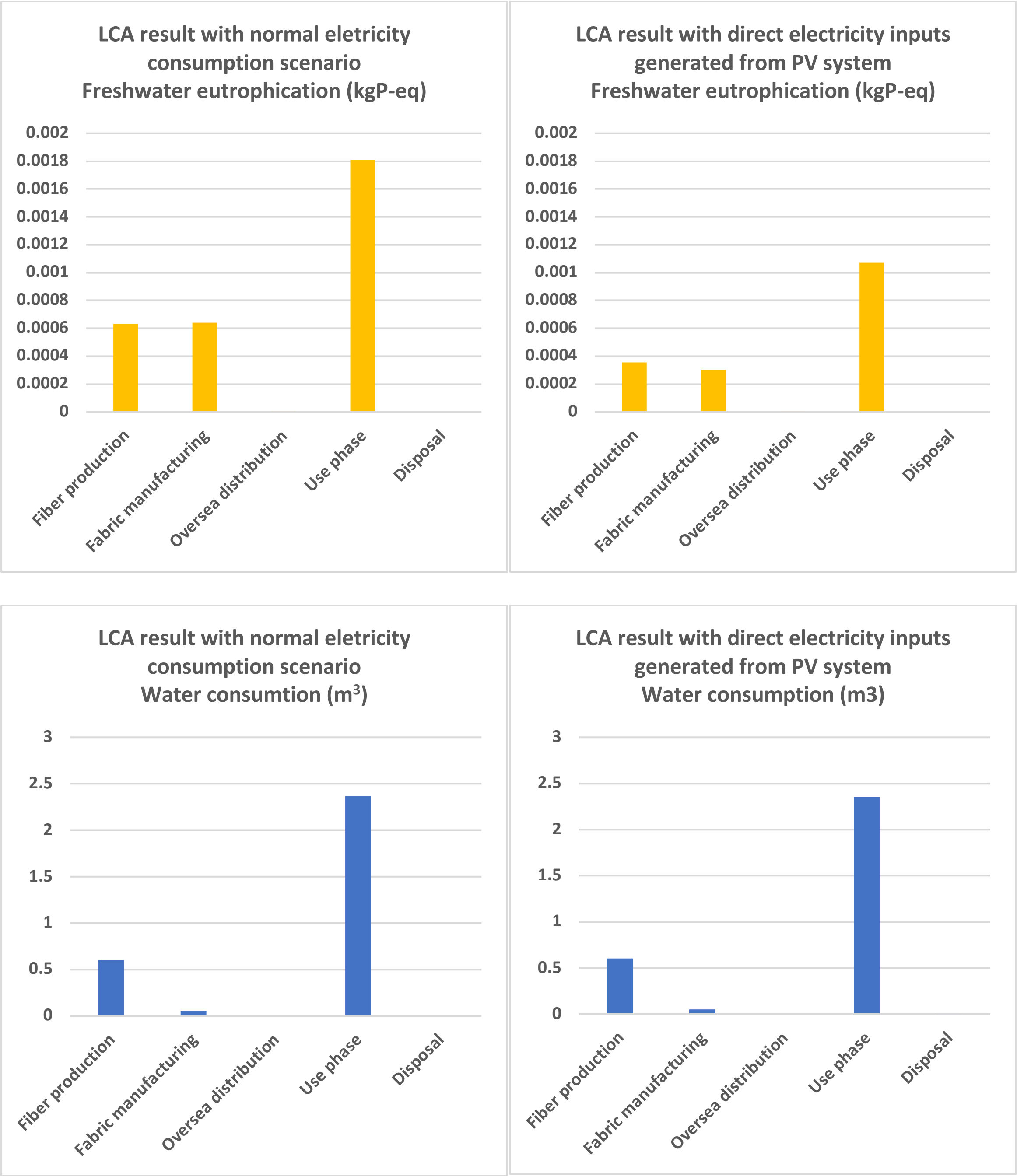


Figure 17: Comparison of the LCA results of cotton T-shit US-CN-NL between the current electricity consumption scenario (left) and the renewable electricity consumption scenario (right), where all the direct electricity inputs in the LCI were assumed to be generated from photovoltaic (PV) system.

6.1.3 Uncertainty check

The LCA result shows that use phase had the highest environmental impacts in the lifecycle of both cotton T-shirts, and the most contributive proves in all impact categories comes from the consumption of electricity in the washing and tumble drying processes. From the LCI analysis (Section 4.2), the quality of the electricity consumption of the laundry and tumble dryer were defined upon the assumption that the product life-time of white goods is around 10 years (Cassidy, 2014). Hence, the quality of electricity consumption should be equal to the quality of the machines in 2008. However, from 2012, Europe applied the Eco-design regulation which banned washing machine and tumble dryer models that have low energy efficiency (Michel et al., 2016), and as a result, all the later models have much higher energy efficiency (see **Table 25** for comparison); for example, the energy consumption of the tumble dryer in 2015 is almost 40% more efficient than the model in 2008. Consequently, it is possible that this significant difference might affect the LCA of the cotton T-shirts.

Table 25: Comparison between the annual energy consumption of the washing machine and tumble dryer among three different periods: 2008, 2012, and 2015. (Michel et al., 2016)

Year	**Energy consumption (kWh/year)**	
	Washing machine	Tumble dryer
2008	226	563
2012	205	453
2015	179	362

Accordingly, to deal with the above uncertainty, another LCA of cotton T-shirt was conducted. This time the energy consumption of 2015's model of the washing machine and tumble dryer were used as inputs, replacing the 2008's models. The rest of the inputs, such as, water consumption and detergent consumption were left unchanged. Since the geographical scope of the use phase of both cotton T-shirt was the same, the Netherlands, there was no point in assessing the impact of both products. Therefore, only the LCA of T-shirt US-CN-NL was analyzed.

Figure 18 shows the comparison between the LCA of T-shirt US-CN-NL that was washed and dried by the machine in 2008 and 2015. From the result, the increased in energy efficiency substantially reduced the environmental impacts of the cotton T-shirt, particularly on climate change and freshwater eutrophication, up to 16 and 19% respectively. However, it did not have much influence on freshwater consumption. This is because the hydropower electricity – the main cause of water consumption – was mostly used in the production of paper and corrugated board (detergent packaging). Accordingly, when comparing the impact between the two scenario (2008 vs. 2015) from the whole life-cycle perspective, the overall conclusion did not change. The use phase remained to be the most contributing factor overall.

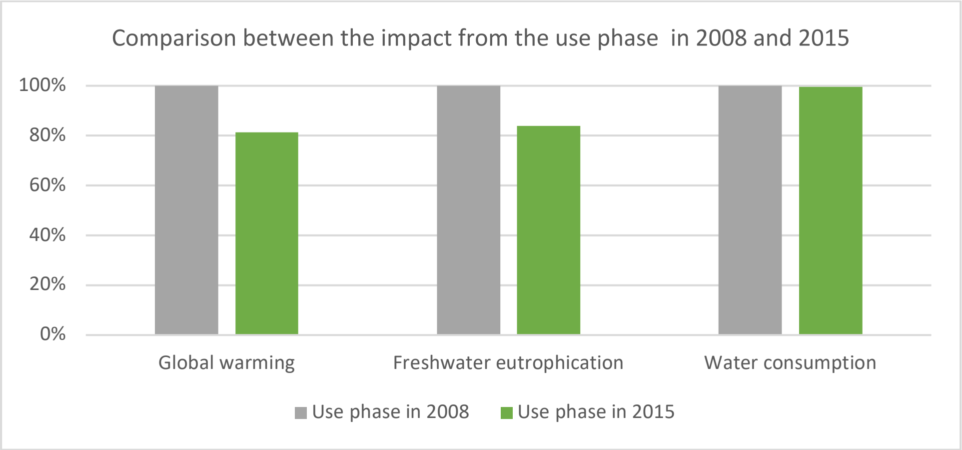
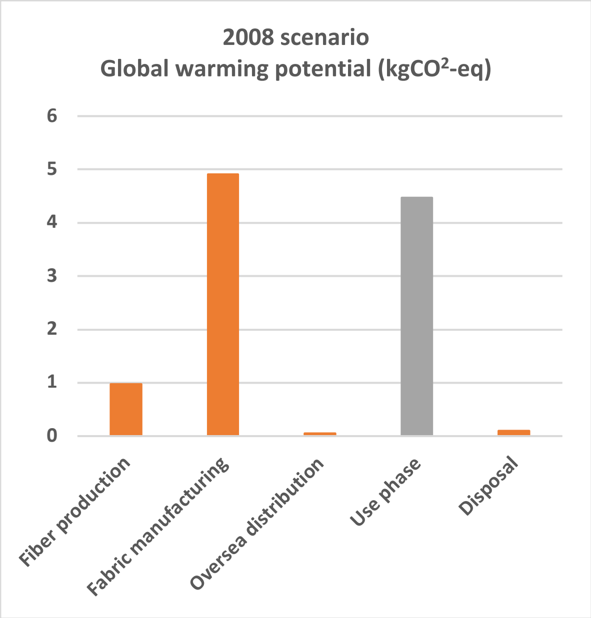
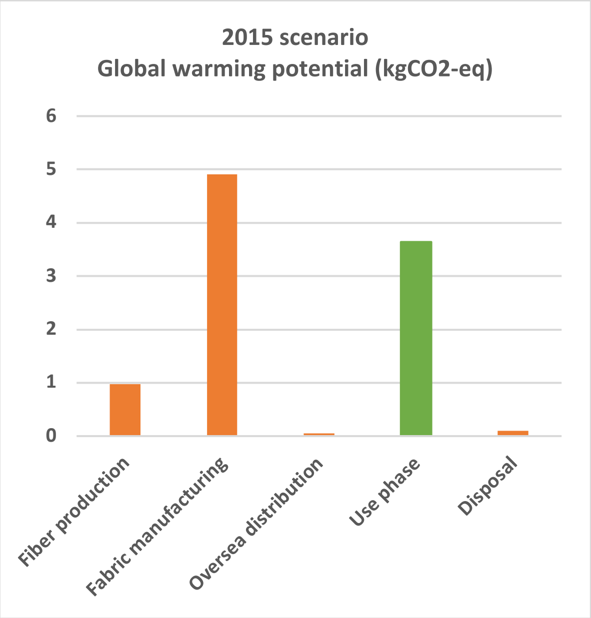
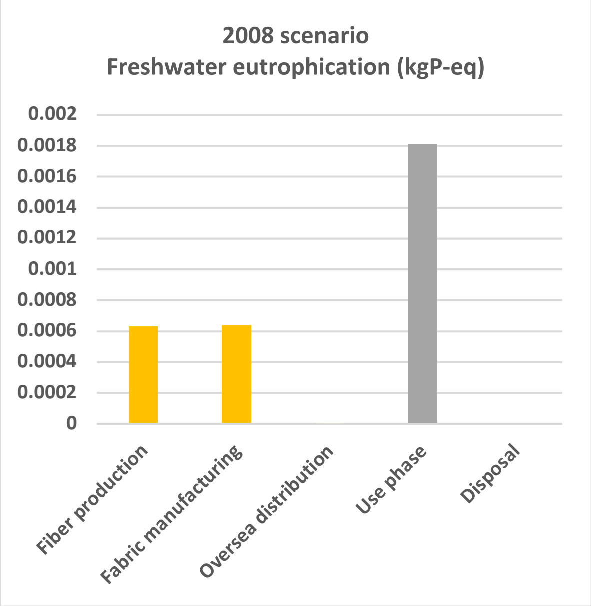
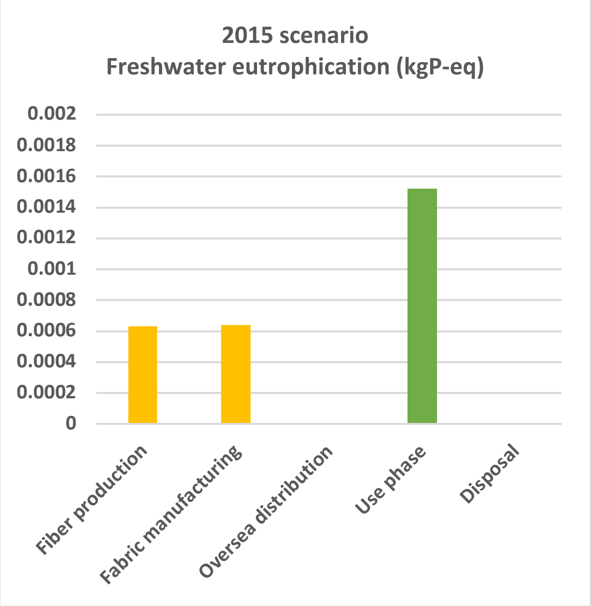


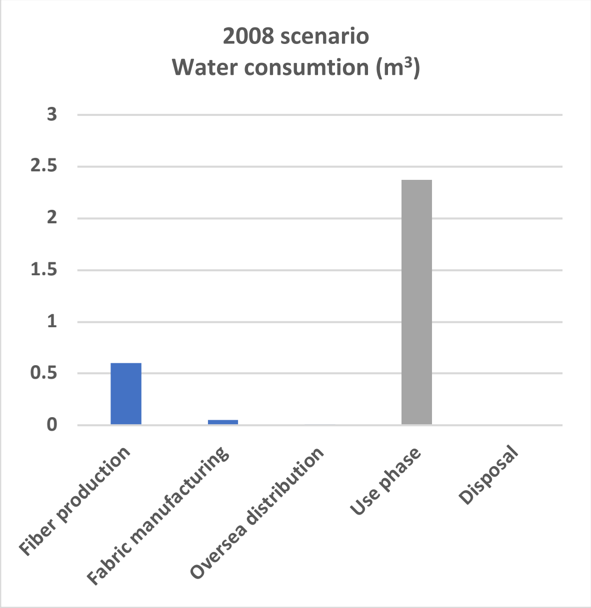
Figure 18: Comparison between the impact assessment result for use phase in 2008 and 2015 with a difference in machine's energy efficiency


2008 scenario
Global warming potential (kgCO²-eq)
6
5
4
3
2
1
0
Fiber production
Fabric manufacturing
Oversea distribution
Use phase
Disposal


2015 scenario
Global warming potential (kgCO2-eq)
6
5
4
3
2
1
0
Fiber production
Fabric manufacturing
Oversea distribution
Use phase
Disposal


2008 scenario
Freshwater eutrophication (kgP-eq)
0.002
0.0018
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
Fiber production
Fabric manufacturing
Oversea distribution
Use phase
Disposal


2015 scenario
Freshwater eutrophication (kgP-eq)
0.002
0.0018
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
Fiber production
Fabric manufacturing
Oversea distribution
Use phase
Disposal


2008 scenario
Water consumtion (m³)
3
2.5
2
1.5
1
0.5
0
Fiber production
Fabric manufacturing
Oversea distribution
Use phase
Disposal

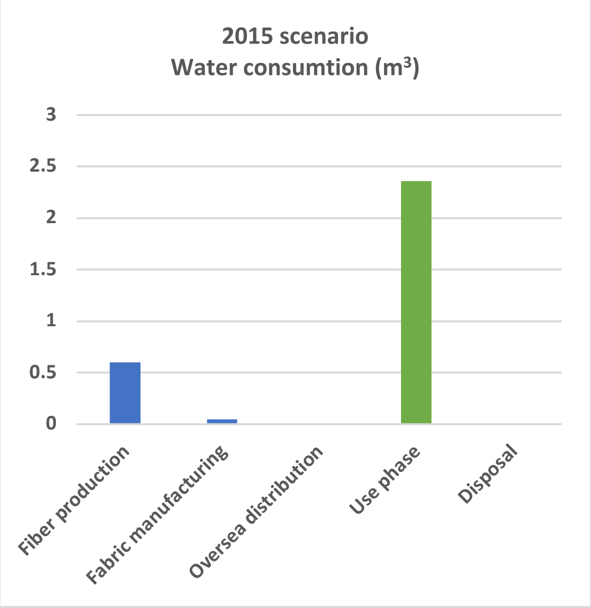

2015 scenario
Water consumtion (m³)
3
2.5
2
1.5
1
0.5
0
Fiber production
Fabric manufacturing
Oversea distribution
Use phase
Disposal

Figure 19: Comparison of the LCA of cotton T-shit US-CN-NL in the scenario between the use of washing machine and tumble dryer in 2008 (left) and 2015 (right).

Additionally, the uncertainty in the use behavior in term of cloth washing and drying frequency was also conducted. The aim was to explore the influence of reduction in washing and drying, whether the factor had more influence than the improvement in electricity efficiency or not. Similarly to the above uncertainty analysis, cotton T-shirt US-CN-NL was chosen as a sample. The efficiency of the washing machine and tumble dryer were from 2008 period, while the rate of washing and drying were assumed to be decreased by half (50%) – 25 washing cycles and 6 drying cycles.

Figure 20 shows the comparison between the LCA of T-shirt US-CN-NL that was washed and dried in normal use behavior – 50 washing cycles & 12 drying cycles within one year – and the LCA of the same T-shirt but was washed and dried with 50% reduction in frequency – 25 washing cycles & 6 drying cycles with one year. It shows that the reduction significantly lowered the environmental impact of the cotton T-shirt by 50% in all categories, much more effective than the increase in energy efficiency of the machines. Furthermore, as T-shirt was washed less, the amount of the laundry detergent use also decreased by half. And since most of the water consumption in this phase came from the hydropower electricity consumption used in the manufacturing process of corrugated board and paper-wood for detergent packaging, the amount of water consumption was also reduced by half. This is an outcome in which an improvement in energy efficiency of the washing and tumble drying machines could not mitigate. Thus, the overall result indicates that the change in use behavior can substantially reduce the impact in all three categories.

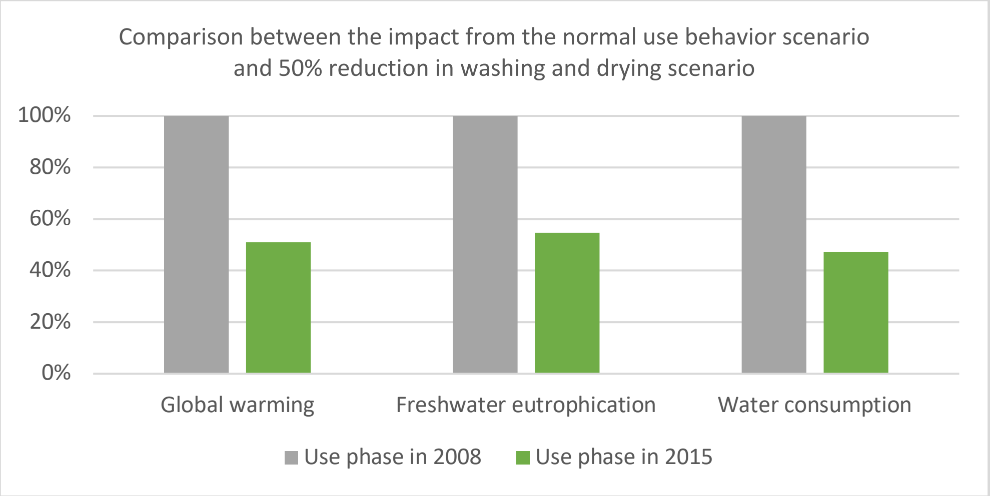
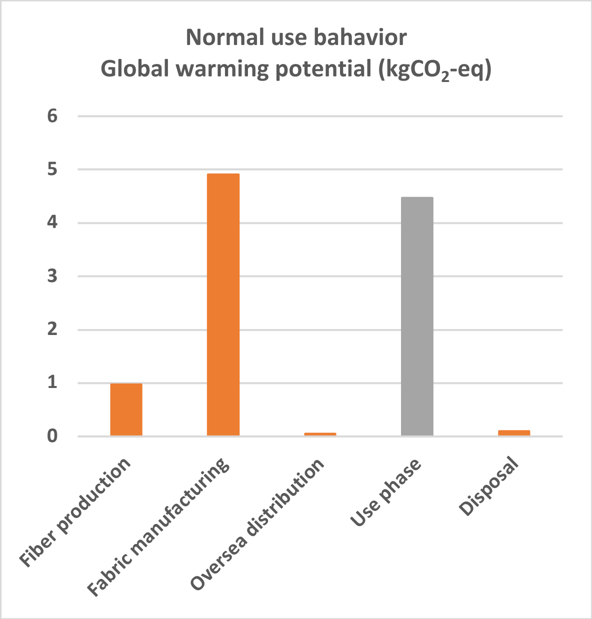
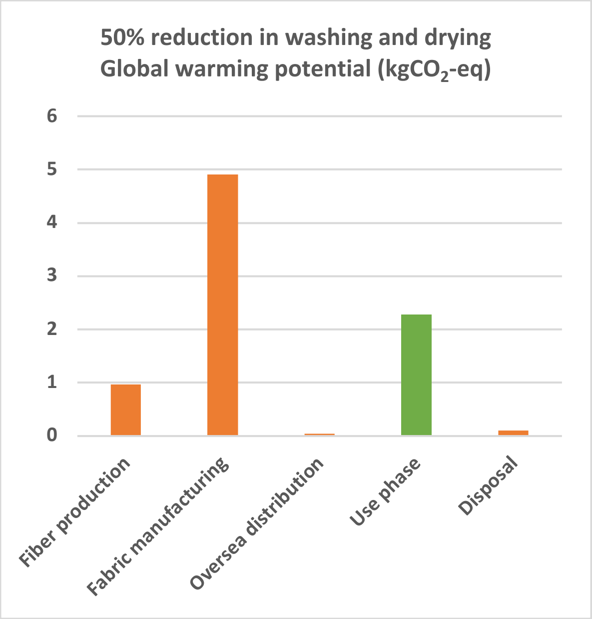
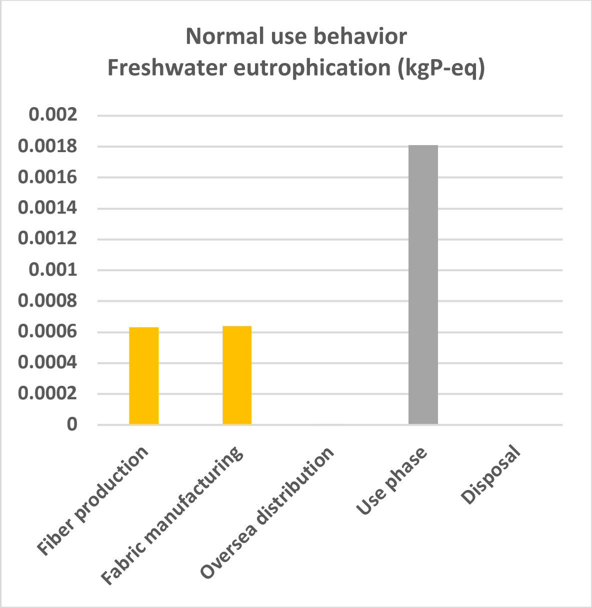
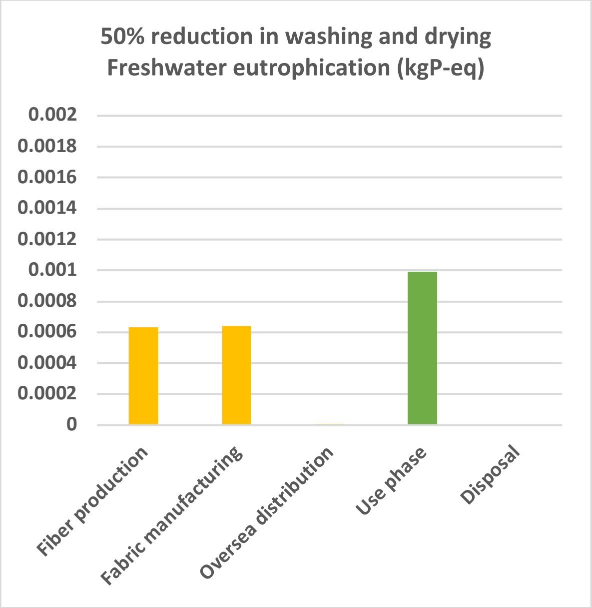


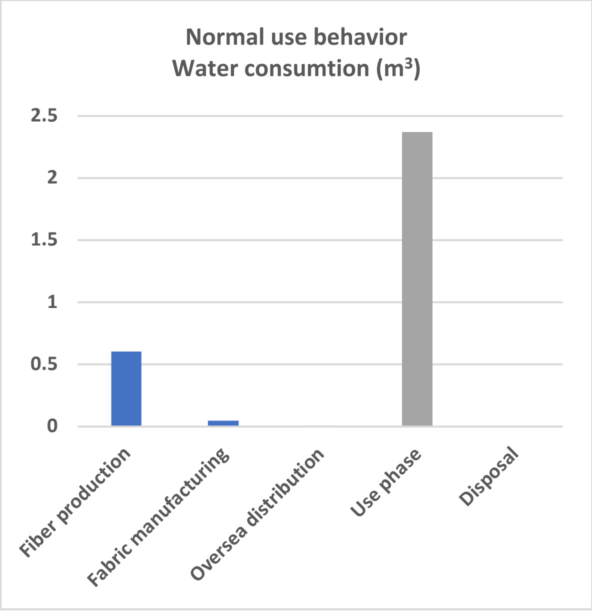
Figure 20: Comparison between the impact from the normal use behavior scenario and 50% reduction in washing and drying scenario


Normal use bahavior
Global warming potential (kgCO2-eq)
6
5
4
3
2
1
0
Fiber production
Fabric manufacturing
Oversea distribution
Use phase
Disposal


50% reduction in washing and drying
Global warming potential (kgCO2-eq)
6
5
4
3
2
1
0
Fiber production
Fabric manufacturing
Oversea distribution
Use phase
Disposal


Normal use behavior
Freshwater eutrophication (kgP-eq)
0.002
0.0018
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
Fiber production
Fabric manufacturing
Oversea distribution
Use phase
Disposal


50% reduction in washing and drying
Freshwater eutrophication (kgP-eq)
0.002
0.0018
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
Fiber production
Fabric manufacturing
Oversea distribution
Use phase
Disposal


Normal use behavior
Water consumtion (m3)
2.5
2
1.5
1
0.5
0
Fiber production
Fabric manufacturing
Oversea distribution
Use phase
Disposal

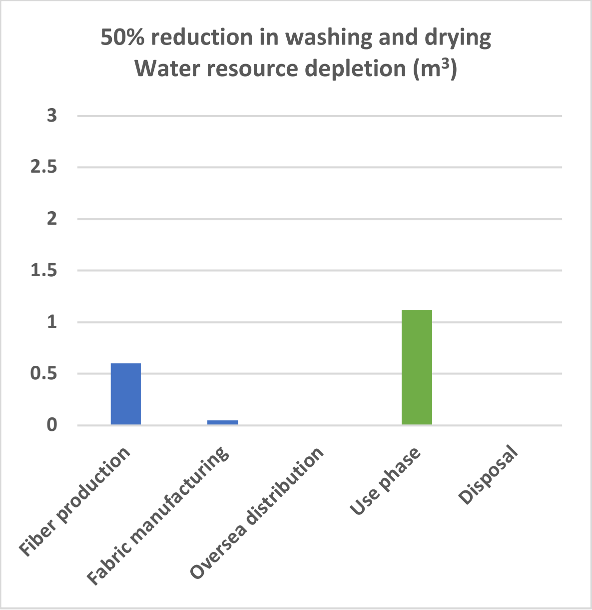

50% reduction in washing and drying
Water resource depletion (m3)
3
2.5
2
1.5
1
0.5
0
Fiber production
Fabric manufacturing
Oversea distribution
Use phase
Disposal

Figure 21: Comparison of the LCA of cotton T-shit US-CN-NL between the normal cloth use behavior scenario – 50 washing cycles and 12 drying cycles (left) – and 50% reduction in washing and drying scenario – 25 washing cycles and 6 drying cycles (right)

6.2 The impracticality of impact reduction in according to the reduction targets

Although the implications from applying the impact-reduction target to the lifecycle environmental impact of cotton T-shirts have already been described in Section 5.3, the question whether clothing companies can realistically make used of the result still remains unanswered. Thus, in this section, the practicality issues of the implications for textile companies are going to be discussed.

Assuming that textile companies decided to adopt the impact reduction target, it is questionable whether they can realistically achieve such drastic impact reduction. According to Beton et al. (2014), who assessed 11 current improvement options for impact reduction throughout the whole lifecycle of textile products (from cradle to grave) in Europe (**Table 26**), their study concludes that the maximum rate of impact reduction (in total) for the whole lifecycle after combining all the intervention together, has a range between 17-51% for different impact categories – these numbers were based on the baseline scenario in their study (**Figure 22**). Specifically, the maximum rate for climate change, freshwater eutrophication, and water consumption is 22%, 28%, and 35% respectively. When comparing these numbers with the impact reduction targets identified under Sandin's procedure, the comparison reveals a significant gap between the reduction target and technology capability. This might also explains why, in the case study of Sandin et al. (2015), they set year 2050 as the time horizon for reducing the environmental impact down to the reduction targets – so that there is room for the development of technological innovations as well as market transformation (Grübler, 2003).

Table 26: List of improvement options throughout the life-cycle that were included in the assessment of impact reduction in Beton et al. (2014).

Phase	Included improvement option
Production	Replacement of traditional cotton by GM cotton
	Reducing the consumption of sizing chemicals
	Use of fully fashioned knitting
	Use low liquor ratio dyeing machines and dye machine controllers
	Recycling of effluent water by ion exchange technology
Distribution	Avoidance of air transportation
Use	Reduction of the washing temperature
	Increase of the load capacity of washing and drying appliances
	Reduction of the use of tumble drying
	Improvement of washing machines and dryers efficiencies
Disposal	Increase of the collection of used clothing for reuse and recycling

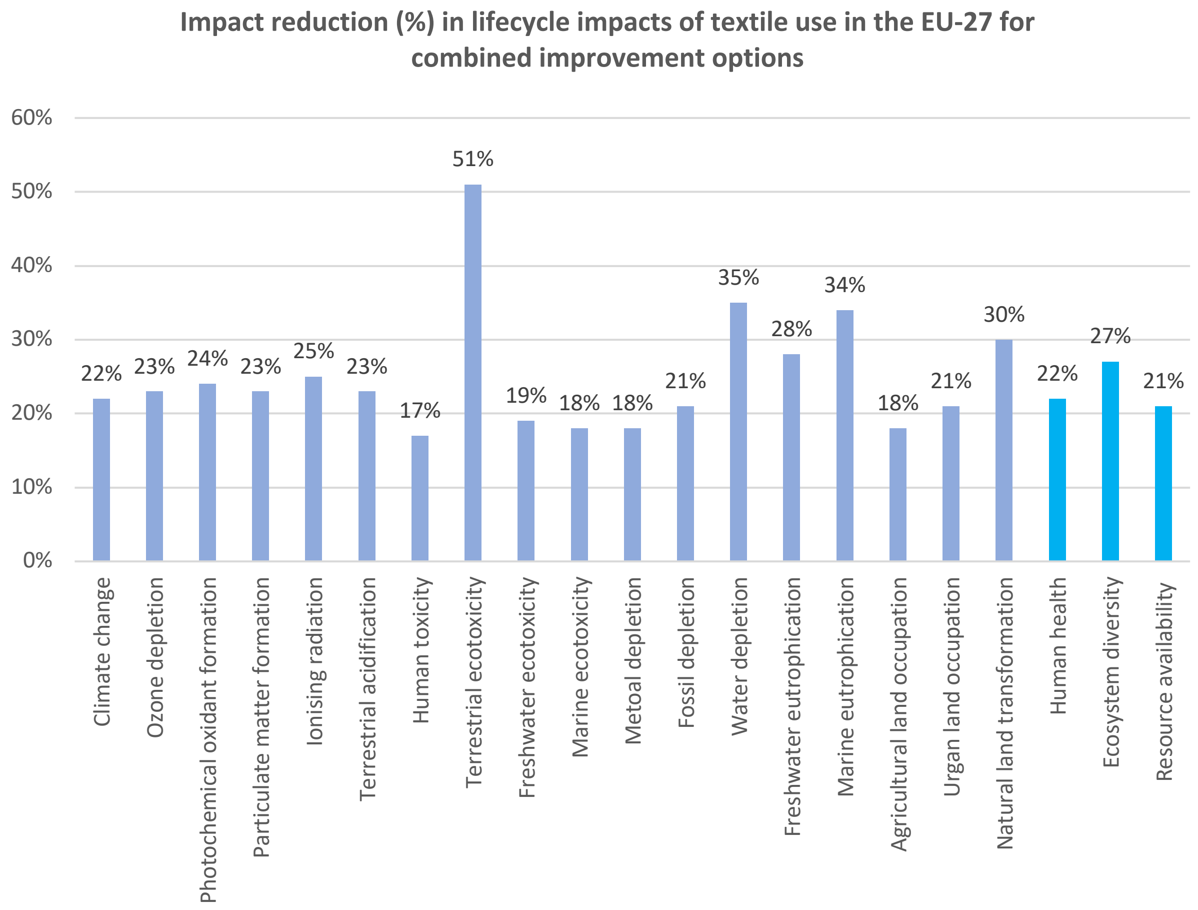


Figure 22: Impact reduction for the whole lifecycle of textile use in the EU-27 for combined improvement options across different impact categories (both midpoints & endpoints), compared to the baseline scenario from the study of Beton et al. (2014)

Nonetheless, given the time horizon and advance technological development of textile industry, it still unlikely for companies to achieve some targets, as the problems are sometimes beyond the control of the companies, even for their suppliers. The analysis of process contribution in the lifecycle impact assessment suggests that tackling the electricity consumption within the elementary flow of the product system would significantly reduce the environmental impacts throughout the value chain, as the process is majorly responsible in many impact categories, depending on the energy source. However, the companies do not have the authority to freely choose the appropriate source of electricity as the decision is not within their control; they can only improve their consumption efficiency. Therefore, to achieve the targets, an overall transformation across industries is required.

In conclusion, no matter how urgent the problems had the impact-reduction targets addressed, but without large technological innovation and cross-industrial transformation towards environmental impact reduction, the idea of using the targets as the quantitative goal for textile companies is still unrealistic. For this reason, it might be more logical to apply Sandin's procedure in the country level than one particular business sector.

6.3 The limitations in linking Sandin's procedure with the LCA of a product

In this section, the discussion focuses on the scientific limitations of linking the impact-reduction target developed based on PB framework to the LCA of products, which then results in the impracticality of the application.

There are four main issues that limit the practicality of applying Sandin's procedure to the LCA of the product. These are 1) the inconsistency between the PB's control variables and LCA's impact categories, 2) The exclusion of many LCA impact categories, 3) the absent of regionalized planetary boundaries, and 4) Challenges in developing the allocation factors ($\mathbf{A}_{\mathbf{market,\,Y}}$ and $\mathbf{A}_{\mathbf{region,\,Z}}$)

6.3.1 Inconsistency between the PB's control variables and LCA's impact categories

It is important to realize that PB and LCA framework were not originally designed to be compatible with each other. On one hand, the objective of PB-framework is to identify numbers of essential earth system's process, their safe-operating space and currently known condition, in order to maintain the Holocene-like state (Steffen et al., 2015). On the other hand, the objective of LCA-framework is to assess the environmental impact in according to the functional unit, throughout the life-cycle of a product, and to identify where those impacts occur (ISO, 2006). Thus, it is not incomprehensible if there is an inconsistency between the two framework.

The problem with using PB within the LCA framework is that not all PBs are directly aligned with LCA impact categories (Ryberg, Owsianiak, Richardson, & Hauschild, 2016), despite the fact that there are certain correlation between the control variables of the PB and the indicator of each LCA impact category (midpoint). **Table 27** shows the control variable of the PBs and the indicators of the LCA impact categories that Sandin et al. considered a proper match (Sandin et al., 2015), and were studied in the case-study. The data on the impact indicators were taken from ReCiPe 2016 (Huijbregts et al., 2017).

Table 27: The control variable of the PBs and the indicators of the LCA impact categories that were studied in the case study, of which Sandin et al. (2015) considered the each particular PB and LCA impact category to be a proper match.

No.	PB framework			LCA framework	
	Earth system processes	**Control variables**		**Indicator**	**Impact categories**
1	Climate change	Atmospheric CO_2 concentration	**Matched PB and LCA impact category in according to Sandin et al. (2015)**	Increase of infrared radiative force	Climate change
		Energy imbalance at top-of-atmosphere (change in radiative forcing)			
2	Biogeochemical flows: Phosphorus flows	Annual rate of phosphorus flow from fertilizers to erodible soils		Phosphorus increase in freshwater	Freshwater eutrophication
3	Freshwater use	Annual consumptive blue water use (global)		Increase of water consumed	Water consumption

As can be seen, there are some inconsistencies between many control variables and the indicators. For example, the indicator for the freshwater eutrophication according to ReCiPe method is the phosphorus concentration in freshwater source, while the regional control variable of the phosphorus flow (one of the PBs for biogeochemical flows) is the phosphorus inputs as fertilizers to soils, which is rather an inventory than an impact from the LCA perspective.

Another example is the planetary boundary for climate change. While the control variable of the changing in radiative forcing is aligned with the indicator for LCA impact category of climate change, the atmospheric CO_2 concentration which is another control variable for climate change's PB is not perfectly the same as the indicator. Hence, it is inappropriate to directly match certain control variables of the PBs with the LCA impact categories.

The last example, yet equally important one, is the inconsistent between the control variable of the freshwater use (PB) and the water consumption behavior in reality. In the PB-framework, the control variable for freshwater use specifically focuses on the consumptive blue water use in river sources, because Rockström et al. consider it as the proxy for "*the full complexity of the highest risk for global water thresholds*" (Rockström et al., 2009b, p. 15). However, in reality, many human activities consumed blue water in other freshwater sources as well, such as, groundwaters and lakes. It might be inappropriate to apply the threshold for consumptive blue water use in river runoff only to the consumption of all blue water sources combined in real practice. Furthermore, it is still questionable whether the number of global consumptive use of river runoff used in Rockström et al. (ibid.) could be that small – 2,600 km^3 yr^{-1} (Shiklomanov & Rodda, 2003) – when the new studies on the recent global blue-water consumption all estimated the number to be above 1000 Gm^3 yr^{-1} (Mekonnen & Hoekstra, 2011b; Wang & Zimmerman, 2016)

However, recently, researchers had proposed a suggestion for tackling these misalignment issue. In May 2018, Ryberg and his colleagues published a study proposing a new "*life-cycle impact assessment (LCIA) methods which allow for expressing indicators of environmental impact in metrics corresponding to those of the control variables in the Planetary Boundaries framework*" (Ryberg et al., 2018, p. 250) – this new LCIA method is called by them as 'PB-LCIA'. To be specific, in their study, the authors proposed a framework for calculating the characterization factor (CF) for the control variables in PB framework (except the biosphere integrity and the introduction of novel entities) – see the Appendix. They also developed CFs for a total of 85 elementary flows that they recognized as dominant contributors to the breaching of the PBs, based on their proposed framework.

Additionally, they also conducted a comparative study in order to assess whether the CFs for the PB would yield similar or different impact assessment conclusion from the existing CFs for LCA impact categories or not. According to them, "*10,687 unit processes in the Ecoinvent v.3.1 consequential life cycle unit process database* (Weidema et al., 2013)" (Ryberg et al., 2018, p.256) were chosen to conduct LCIA using both set of CFs (for PBs and LCA impact categories). These unit processes were classified into 4 main segments: material, energy, transport, and processing. The CFs for the PBs that share "*similarities in the environmental pressure and elementary flows*" (ibid.) to the selected LCA impact categories were chosen for comparison. For example, the CF for the photochemical ozone formation in LCA was chosen to compare with the CF for the atmospheric aerosol loading in PB, and the CF for the freshwater eutrophication in LCA was chosen to compare with the CF for the phosphorus flows in PB. Through the two sets of CFs, the impact for each unit process were assessed and then ranked (within each LCA impact category or PB). Correspondingly, the authors used Pearson correlation analysis to evaluate the correlations in term of magnitude between the LCIA results of two CFs sets.

Table 28 shows correlation coefficient (r) from Pearson analysis. As can be seen, the correlation in magnitude between the impact assessment results of CFs for PBs and LCA impact categories were considerably high. The correlation coefficients are above 0.97 for all matched PBs and LCA impact categories, except the PBs for 'land-system change' and 'regional phosphorus cycle', where the results did not have much correlation with the LCA impact category of 'land use' and 'freshwater eutrophication' respectively. The authors explained that this is "*primarily due to a difference in coverage of environmental flows*" (Ryberg et al., 2018, p.258). In freshwater eutrophication, for instance, the CFs for the matched PB (regional phosphorus flow) only consider the emission of phosphorous compounds to surface water (the closest freshwater source to erodible soils, as assumed by Ryberg et al. (2018)), while the CFs for LCA's freshwater eutrophication impact take other emissions routes (i.e. phosphate to groundwater) into consideration as well. Additionally, despite the high correlation between the CFs for freshwater use and water resource depletion, the introduced characterization method for the planetary boundary still did not deal with the inconsistent issue between the control variable (consumptive blue water use threshold for river only) and the behavior of water consumption in reality. Thus, there are still rooms for further development in the characterization method for CFs of certain PBs. Moreover, the authors also mentioned by themselves that the proposed method is still a "*proof-of-concept and that further testing and validation is required before the method can be considered as mature*" (Ryberg et al., 2018, p.261).

Table 28: Pearson analysis between the introduced CFs for the PB and the CFs for the LCA impact category (Ryberg, Owsianiak, Richardson, & Hauschild, 2018b, p. 54). The closer the coefficient is to 1, the higher the correlation it represent.

LCA impact category	**Control variable in PB**	**Rationale for comparing impact categories**	**Pearson correlation coefficient (r)**	**Spearman rank correlation coefficient (r_s)**
Climate change	Climate change - CO_2 concentration	"*Both express climate change*" (Ryberg et al., 2018b, p.54)	**1.00**	**0.99**
Climate change	Climate change - Energy imbalance	"*Both express climate change*" (Ryberg et al., 2018b, p.54)	**1.00**	**0.99**
Climate change	Ocean acidification	"*Ocean acidification is linked to the drivers of climate changes because ocean acidification is a consequence of anthropogenic CO_2 emissions* (Doney, Fabry, Feely, & Kleypas, 2009; Feely et al., 2004)." (Ryberg et al., 2018b, p.54)	**1.00**	**0.99**
Ozone depletion	Stratospheric ozone depletion	"*Both express ozone depletion.*" (Ryberg et al., 2018b, p.54)	**0.97**	**0.99**
Land use	Land-system change – Global	"*Both express land use.*" (Ryberg et al., 2018b, p.54)	**0.27**	**0.85**
Water resource depletion	Freshwater use - River basins	"*Both express freshwater use.*" (Ryberg et al., 2018b, p.54)	**0.93**	**0.89**
Photochemical ozone formation	Atmospheric aerosol loading	"*The PB was compared with "Photochemical ozone formation" because both include emissions of aerosols to the atmosphere. However, the area of concern for the two indicators differ slightly, where "Photochemical ozone formation" is about ground level ozone formation (and concentration) and how this affects humans and ecosystems* (EC-JRC, 2010; M. Z. Hauschild & Huijbregts, 2015; van Zelm, Preiss, van Goethem, Van Dingenen, & Huijbregts, 2016)*, while "Atmospheric aerosol loading" is about aerosols in the atmosphere and how the increased loading may lead to*	**0.98**	**0.91**

		undesired effects due to changes in solar radiation and regional ocean-atmosphere circulation (Steffen, Richardson, Rockström, Cornell, Fetzer, Bennett, Biggs, Carpenter, De Vries, et al., 2015a). *Hence, the two impact categories differ in their area of concern; however, they have been compared in this study due to their similarities in impact pathway and to allow a comparison of results for aerosols between* [PB's control variables] *and* [LCA impact category]." (Ryberg et al., 2018b, p.54)		
Freshwater eutrophication	Biogeochemical flows - Regional P	"*The PB was compared with "Freshwater eutrophication" because in majority of LCIA methods, phosphorus is considered the primary contributor to freshwater eutrophication* (EC-JRC, 2011; Goedkoop et al., 2013). *This is because phosphorous is the predominant growth-limiting nutrient for freshwater ecosystems* (Carpenter et al., 1998; Schindler, 1977; Smith, 2003) *and thus most problematic in terms of freshwater eutrophication*."	**0.51**	**0.61**
Marine eutrophication	Biogeochemical flows – N	"*The PB was compared with "Marine eutrophication" because in majority of LCIA methods, nitrogen is considered the primary contributor to marine eutrophication* (Cosme, Koski, & Hauschild, 2015; EC-JRC, 2011; Goedkoop et al., 2013). *This is because nitrogen is, in many cases, the predominant growth-limiting nutrient for marine ecosystems (i.e. estuaries and coastal systems)* (Carpenter et al., 1998; Howarth & Marino, 2006; Vitousek, Hättenschwiler, Olander, & Allison, 2002) *and thus most problematic in terms of marine eutrophication."* (Ryberg et al., 2018b, p.54)	**0.97**	**0.95**

6.3.2 The exclusion of other LCA impact categories

Despite being first published in 2009, the research on the PB-framework is still considerably novel. Not all the PBs have been quantitatively defined yet, which thus explains why many impact categories are excluded from the proposed procedure of Sandin et al. (2015). For example, it is impossible to develop the impact-reduction target for the impact related to chemical-use in textile industry (ecotoxicity) as the most relevant boundary – the introduction to novel entities – has yet to be quantified.

Furthermore, the area of protection in LCA is different and broader than the area of protection in the PB. While the LCA framework consider the environmental impact towards human health, biotic and abiotic natural environment, the PB focus on the natural environment only – maintaining the essential Earth system's processes to ensure the existence of the Holocene state. As a result, many impact categories related to human health are excluded (Ryberg et al., 2016).

6.3.3 The absent of regionalized boundaries.

Another issue which jeopardize the practicality of the impact-reduction target, is the absence of regionalized boundaries in the PB-framework (Rockström, Steffen, Noone, Åsa, et al., 2009a; Steffen, Richardson, Rockström, Cornell, Fetzer, Bennett, Biggs, Carpenter, De Vries, et al., 2015a). Many Earth System processes in the PB-framework tend to have regionalized thresholds. For instance, there should be a regional threshold for each river basin and land conversion. However, the currently proposed PBs are generally for the global level only. Even if there are some regional level PB, they are not contextualize to any specific region. Without regional boundaries, there are chances that the impact-reduction target might not reflect an appropriate reduction target to the impact of the product. On the contrary, there has been more development in the regionalization of the characterization factors for some LCA impact categories, likes freshwater use (Ansorge & Beránková, 2017). This allows the impact assessment of the product to take the regional context into account, while the impact-reduction target from Sandin's procedure does not (Sandin and colleagues also mentioned this limitation themselves (Sandin et al., 2015)).

6.3.4 Challenges in developing the allocation factors ($A_{market,\,Y}$ and $A_{region,\,Z}$)

Aside from the challenge of translating the PB to impact categories in LCA, there are also limitations of the allocation methods in Sandin's procedure, both for the specific market segment ($\mathbf{A_{market,\,Y}}$, Perspective A-C) and geographical scope ($\mathbf{A_{region,\,Z}}$, ethical Principle 1-4).

First of all, there is a need for a proper methodology in developing the proxy to justify the share of impact of a product in a market segment (Perspective A-C), as the given values for a product that deserve equal share, half share, or twice the share of impact are simply a rule of thumb. Future research into the development of well-found set of indices for determining the allocation factor of different market segment, would greatly contribute to the improvement of Sandin's procedure.

Moreover, unlike the case study of Sandin et al. (2015), whose the case study focused on reducing the impact of the finished product, this thesis developed the impact-reduction target throughout the whole value chain of cotton T-shirts. The result of the study raises an important question whether should we still use the Perspective A-C, which talks about a finished product, to justify the share of impact for all the processes in the product's value chain – if a cotton T-shirt deserve only half of the globally allowed impact for an impact category, does the process of fiber production also deserve the same share, even though the activity might be valuable to the local economic wealth? Or when there is also other by products from the same activity but are used to produce another product of different market segment, which impact-reduction target should the activity set as goal? These questions, thus, addressed the need for a better defined method and consensus before the procedure could be put into real practice.

In the allocation method for different geographical scope, using ethical principles, the limitation of Principle 2, 3, and 4 has already been pointed out by Sandin et al. themselves (Sandin et al., 2015) – see Section 3.3.3. As for Principle 1, one of the main issue lies within the variables used to calculate the allocation factor; these are the global and national population ($\boldsymbol{P_{GloCur}}$ and $\boldsymbol{P_{GloFut}}$) in the future, and the global and national average per capita impact ($\boldsymbol{I_{Glo}}$ and $\boldsymbol{I_{Reg}}$). For the populations, the allocation factor is subjected to the accuracy of the estimated future population. The time horizon of 2050 is a long period from the present; there are chances in which the estimation could be revised multiple times as the world arrives closer to the time horizon. As for the average per capita impacts, the choice of choosing the type of impact data to represent 'average per capita impacts' extremely influences the allocation factor, possibly even more than the population ratio ($\boldsymbol{P_{GloCur}}$ / $\boldsymbol{P_{GloFut}}$). For example, in the case-study of Sandin et al. (2015), they used the green and blue water footprint data to identify the average per capita impact of freshwater use ($\boldsymbol{I_{Glo}}$ / $\boldsymbol{I_{Reg}}$), while in this case-study, only the blue water footprint data was used. **Table 29** shows the result between the impact-reduction targets of freshwater consumption that used both green-blue water footprint, and blue footprint only. As can be seen, the result shows substantial differences the target for China and the Netherlands. Therefore, further research on the revision of possible variables to be used in the allocation factor of $\mathbf{A_{region,\,Z}}$ in each planetary boundary is recommended.

Table 29: The impact-reduction targets of freshwater consumption in Perspective B & Principle 1 when using both green and blue water footprint, and when using only blue water footprint as the variable to calculate (I_{Glo} and I_{Reg}). The source of both type of water footprint was taken from (Mekonnen & Hoekstra, 2011a)

	Impact-reduction targets (in %)		
	China	The United States	The Netherlands
Green & blue water footprint	15	68.5	41.3
Blue water footprint only	22.2	62	29

7. Conclusion

In this thesis, Sandin's procedure was used to develop the impact-reduction target for a clothing product. The reduction targets were then applied to an LCA case-study of cotton T-shirts (cradle to grave). The main objective was to explore potential applications for clothing companies to incorporate the result into their sustainability management.

Therefore, the research question of this thesis was structured as followed:

"By applying the impact-reduction targets from Sandin's procedure to the LCIA of cotton clothes in the Netherlands, what are the implications for impact reduction strategy along the value chain of clothing companies?"

Accordingly, the result of the study reveal the implication for clothing companies to use the result as a support when making impact reduction strategy along the value chain of their business. These are, for example, to prioritize the environmental impact of a product, and to prioritize future location for business development. In the case-study of this thesis, the result indicated an advantageous position for business development in China, where the impact-reduction targets are lower than in the United States. Clothing companies that currently sell T-shirt US-CN-NL should prioritize in reducing the water consumption in the fiber production rather than the use phase (despite having lower consumption), as the impact-reduction target of the process is twice higher than the use phase. Overall, the impact reduction on climate change and freshwater eutrophication should be most prioritized in both products, especially in the fabric manufacturing and the use phase, because the two processes has the highest impact contribution as well as the impact-reduction targets. However, the result is not recommended to be used for setting quantitative goal as many of the targets are impractical to achieve, both in term of technological interventions and cross-industrial transformation.

Furthermore, currently there are multiple limitations in the concept of applying Sandin's procedure to the LCIA of products, that makes the concept impractical to be used in real practice. These limitations are related to the incompatibility between the PB and LCA framework (including the exclusion of many LCA impact categories), the absence of regionalized boundaries, and the lack of more concrete allocation method in Sandin's procedure. Tackling these limitations should be the first step to realizing the practicality of Sandin's procedure. Hence, further research recommendations are described below:

- Improving the compatibility between PB and LCA framework – further testing and validation of the set of the characterization factors for the control variables of PBs introduced by Ryberg et al. (2018) could be one of the research trajectories.
- Exploring whether there is a need to find an absolute boundary for the currently excluded LCA impact categories or not.
- Developing the framework for identifying the regional boundary in according to different geographical context.
- Designing a concrete set of indices for calculating the allocation factor for specific market segment.

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Appendix

Table 30: Characterization modelling for each control variable in the Planetary Boundaries proposed by Ryberg et al. (2018). The information in this table are entirely taken from the published paper of the author (Ryberg et al., 2018a, p.252)

Earth system process	Control variable	Planetary boundary	Governing characterization factor equation	No. of elementary flows covered
Climate change	Energy imbalance at top-of-atmosphere [Wm^{-2}] relative to pre-industrial level	1	$CF_{GW,RF,x}\left[\frac{Wm^{-2}}{kgyr^{-1}}\right] = \frac{\Delta RF}{\Delta S_{GHG,x}}$ Where RF is radiative force [Wm^{-2}] , and $S_{GHG,x}$ is annual emission of GHG x [kg yr^{-1}].	18
	Atmospheric CO$_2$ concentration [ppm CO$_2$]	350	$CF_{GW,CO2conc,x}\left[\frac{ppm}{kgyr^{-1}}\right] = \frac{\Delta CO_{2,atmosphere}}{\Delta S_x}$ Where $CO_{2,atmosphere}$ is atmospheric CO$_2$ concentration [ppm CO$_2$] and S_x is annual emission of CO$_2$ or CO$_2$-precursors [kgyr^{-1}].	7
Stratospheric ozone depletion	Stratospheric O$_3$ concentration in Dobson Units [DU]	5% reduction relative to a pre-industrial level of 290 DU (= 275 DU)	$CF_{OD,x}\left[\frac{DU}{kgyr^{-1}}\right] = \frac{\Delta \lvert C_{O3} \rvert}{\Delta EESC} \times \frac{\Delta EESC}{\Delta TCL} \times \frac{\Delta TCL}{\Delta S_x}$ Where $\lvert C_{O3} \rvert$ is the absolute difference between pre-industrial stratospheric ozone concentration and stemming from a change in equivalent effective stratospheric chlorine level, EESC [ppt]. TCL is total tropospheric chlorine loading equivalent [ppt] and S is annual emission of ozone depleting substance [kgyr^{-1}].	16
Ocean acidification	Carbonate ion concentration, with respect to aragonite saturation state	2.75	$CF_{OA,x}\left[\frac{\frac{mol^2m^{-3}}{mol\,m^{-3}}}{kgyr^{-1}}\right] = \frac{\Delta \lvert \Omega_{Arag} \rvert}{\Delta CO_{2,atmosphere}} \times \frac{\Delta CO_{2,atmosphere}}{\Delta S_x}$ Where $\lvert \Omega_{Arag} \rvert$ [mol^2 m^{-3}/ mol m^{-3}] is the absolute difference between pre-industrial Ω_{Arag} (= 3.44) and the Ω_{Arag} result from a change in atmospheric CO$_2$ concentration. $CO_{2,atmosphere}$ is atmospheric CO$_2$ concentration [ppm CO$_2$] and S_x is annual emission of CO$_2$ or CO$_2$-precursors [kgyr^{-1}].	7
Biogeo-chemical flows (Phosphorus flow)	Global: Phosphorus flow from freshwater system to ocean [Tg P yr^{-1}]	11	$CF_{p,global}\left[\frac{Tg_{marine}yr^{-1}}{kg_{P\ emitted}\ yr^{-1}}\right] = 1 \times 10^{-9} \times \frac{\Delta P_{marine}}{\Delta S_{p-compound\ emitted}}$ Where P_{marine} is annual mass of P outflow to marine waters [kg yr^{-1}] and $S_{p-compound\ emitted}$ is annual mass of P containing compound emitted to the environmental [kg yr^{-1}].	5

	Regional: Phosphorus flow from freshwater system into ocean [Tg P yr^{-1}]	26.2	$CF_{p,regional}\left[\frac{Tg_{applied}yr^{-1}}{kg_{P\ emitted}\ yr^{-1}}\right] = 1\times10^{-9}\times\frac{\Delta P_{applied}}{\Delta S_{p-compound\ emitted}}$ Where $P_{applied}$ is mass of P annually applied to erodible soil [kg yr^{-1}] and $S_{p-compound\ emitted}$ is annual mass of P containing compound emitted to the environmental [kg yr^{-1}].	1
Biogeo-chemical flows (Nitrogen flow)	Global: Industrial and intentional biological fixation of nitrogen [Tg N yr^{-1}]	62	$CF_{N,J}\left[\frac{Tg_{N\ fixed}\ yr^{-1}}{kg_{N\ emitted}\ yr^{-1}}\right] = 1\times10^{-9}\times\frac{\Delta N_{fixated}}{\Delta S_{N\ emitted,j}}$ Where $N_{fixated}$ is mass of annual human induced N fixation [kgyr^{-1}] and $S_{N\ emitted,j}$ is annual mass of N containi=ng compounds emitted to environmental compartment j [kgyr^{-1}].	1
Land-system change	Global: area of forested land as % of original forest cover [%]	75%	$CF_{forest\ global}\left[\frac{\%}{m^2}\right] = \frac{1}{A_{pot,global}}\times 100\%$ Where $A_{pot,global}$ is potential global forest area [10^6 km^2]	1
	Biome: area of forested land as % of potential forest [%]	Tropical: 85% Temperate: 50% Boreal: 85%	$CF_{forest\ biome\_i}\left[\frac{\%}{m^2}\right] = \frac{1}{A_{pot,biome\_i}}\times 100\%$ Where $A_{pot,biome\_I}$ is potential area of forest biome [10^6 km^2]	3
Freshwater use	Global: Maximum amount of consumptive blue water use [km^3 yr^{-1}]	4000	$CF_{freshwater\ global}\left[\frac{km^3yr^{-1}}{m^3yr^{-1}}\right] = \frac{\Delta\, V_{freshwater\ withdrawal}}{\Delta S_{freshwater\ withdrawal}}$ Where $V_{freshwater\ withdrawal}$ is global freshwater volume available for withdrawal [km^{3}yr^{-1}], $S_{freshwater\ withdrawal}$ is annual volume of freshwater withdrawn as a result of human activities [m^3 yr^{-1}]	1
	Basin: Blue water withdrawal as % of mean monthly flow (MMF)	Low-flow month: 25% Intermediate-flow month: 30% High-flow month: 55%	$CF_{freshwater\ use,x}\left[\frac{yr}{m^3}\right] = \frac{\Delta\, WA_x}{\Delta S_{withdrawn,x}}$ Where WA_x is available annual volume of freshwater for human induced withdrawal in spatial archetype x [m^3 yr^{-1}]. Default CFs were based on annual LCI, but CFs with monthly temporal resolution were also developed for LCI with specification on monthly withdrawals.	12
Atmospheric aerosol loading	Global: Aerosol Optical Depth (AOD)	While no Planetary Boundary has been set, CFs for global AOD for global AOD were developed to prepare for a future global Planetary Boundary in the same metric as the regional boundary	$CF_{aerosol,global,x}\left[\frac{dimensionless}{kgyr^{-1}}\right] = \frac{\Delta\, AOD}{\Delta m_{atm}}\times\frac{\Delta m_{atm}}{\Delta S_x}$ Where AOD is aerosol optical depth [dimensionless], m_{atm} is aerosol mass load over global terrestrial area and S_x is annual emission of the aerosol [kg yr^{-1}]	13
	Regional: AOD as a seasonal average over a region with South	0.25	$CF_{aerosol,regional,x}\left[\frac{dimensionless}{kgyr^{-1}}\right] = \frac{\Delta\, AOD}{\Delta m_{atm}}\times\frac{\Delta m_{atm}}{\Delta S_x}$	13

	Asian Monsoon used as case study [AOD]		Where AOD is aerosol optical depth [dimensionless], m_{atm} is aerosol mass load over regional area and S_x is annual emission of the aerosol [kg yr^{-1}]