Chair of Economic- and Business Management

Master's Thesis

Comparative Life Cycle Assessment of Cotton T-Shirt Production: Conventional Global vs. Fully Automated Manufacturing in Europe

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Andrea-Katharina SCHERER, BSc, is given the topic

Comparative Life Cycle Assessment of Cotton T-Shirt Production: Conventional Global vs. Fully Automated Manufacturing in Europe

to work on in a Master's thesis.

In the first section of the master's thesis, the theoretical foundations for dealing with the topic described are to be worked out. In particular, the fashion production sector and its current and future challenges regarding the automation of the overall manufacturing production process are to be presented. Furthermore, the challenges of fashion production regarding the supply chain and the associated supply chain legislation are elaborated. In addition, an overview to life cycle analyses (LCAs) and profitability calculations will be prepared for the practical part of the work.

For the practical part of the thesis, a comprehensive comparative LCA for conventional and automated fashion production is to be developed and presented, taking into account all life cycle phases (cradle-to-grave approach) of both manufacturing routes for fashion. In addition to the LCA, a comparative economic analysis of both manufacturing process chains is to be prepared. This should provide insight into the ecological and economic challenges and potentials of the automation of global fashion production. In the course of this analysis, the findings regarding potential impacts are to be discussed and recommendation are to be derived.

Leoben, 18 September 2023

Univ.-Prof. Dipl.-Ing. Dr. mont. Wolfgang Posch

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Principle of Equality

For reasons of readability, gender-specific formulations have not been used in this paper. It is explicitly stated that the masculine forms used for persons are to be understood for both genders.

Acknowledgment

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Thank you all for being part of this journey. Your support and encouragement have made this achievement possible.

Kurzfassung

Diese Arbeit bietet eine detaillierte Analyse der aktuellen Modeproduktionsprozesse, wobei der potenzielle Übergang von einer halb- zu einer vollautomatischen Bekleidungsproduktion und deren ökologische, aber auch wirtschaftliche Auswirkungen im Vordergrund stehen. Die Forschungsarbeit beginnt mit einer Untersuchung der Entwicklung der Modeindustrie und unterstreicht die anhaltende Abhängigkeit von veralteten Produktionsmethoden und den erheblichen ökologischen Fußabdruck, der durch ausgedehnte Lieferketten und die Herstellung in Niedriglohnländern entsteht.

Unter Verwendung von Methoden der Ökobilanzierung, durchgeführt mithilfe der UMBERTO-Software und den Daten der ecoinvent-Datenbank, vergleicht diese Studie die Umweltauswirkungen eines konventionellen globalen halbautomatisierten Produktionsprozesses mit denen eines europäischen vollautomatischen Prozesses, der Nährobotertechnologie beinhaltet. Dabei wird nicht nur die Produktionskette, sondern der gesamte Lebenszyklus eines Baumwolle T-Shirts von der Wiege bis zur Bahre untersucht. Die Ergebnisse deuten darauf hin, dass die vollständige Automatisierung in Verbindung mit der Verlagerung der Produktion näher an den Verkaufsort die Umweltauswirkungen im Lebenszyklus eines Baumwoll-T-Shirts erheblich verringern kann. Diese Verringerung wird durch geringere Transportemissionen und eine effizientere Ressourcennutzung erreicht, e.g. durch eine Reduktion der derzeitigen Überproduktion um 15%.

Neben der ökologischen Betrachtung wird zusätzlich eine simplifizierte Variante der Rentabilitätsrechnung des Nähroboters zur Automatisierung und die damit verbundenen Auswirkungen einer Verlagerung der Produktion in Hochlohnländer kalkuliert. Obwohl die anfänglichen Investitionskosten für die Automatisierung beträchtlich sind, zeigt die Studie, dass diese durch langfristige Einsparungen bei den Betriebskosten, verbesserte Produktionseffizienz und geringere Abhängigkeit von einer globalisierten Lieferkette ausgeglichen werden könnten.

Darüber hinaus werden auch die sozialen Auswirkungen einer vollautomatisierten Produktion, wie z. B. die mögliche Verdrängung von Arbeitsplätzen und die Notwendigkeit der Umschulung von Arbeitskräften in Hochlohnländern, um die negativen sozialen Auswirkungen der Automatisierung abzumildern. Darüber hinaus werden die rechtlichen Auswirkungen und regulatorischen Anforderungen kritisch bewertet, insbesondere im Hinblick auf neue Richtlinien der Europäischen Union, wie den Digitalen Produktpass und andere Nachhaltigkeitsvorschriften, die bereits in Kraft getreten sind oder gerade überarbeitet werden. Diese rechtlichen Rahmenbedingungen werden eine entscheidende Rolle bei der Gestaltung der Zukunft der Bekleidungsproduktion spielen, da sie mehr Transparenz und Nachhaltigkeit vorschreiben.

Zusammenfassend lässt sich sagen, dass die Umstellung auf eine vollautomatisierte Bekleidungsproduktion sowohl Herausforderungen als auch Chancen mit sich bringt. Sie birgt jedoch großes Potenzial, die Modeindustrie zu revolutionieren, indem sie die Umweltbelastung verringert, die wirtschaftliche Effizienz steigert und im Einklang mit (kommenden) gesetzlichen Anforderungen der EU steht.

Abstract

This thesis provides a detailed analysis of the current fashion production processes, emphasizing the potential shift from semi-automated to fully automated garment manufacturing and its environmental, but also economic implications. The research starts with an exploration of the fashion industry's evolution, underscoring the persistent reliance on outdated production methods and the substantial ecological footprint generated by extensive supply chains and manufacturing in low-wage countries.

Utilizing Life Cycle Assessment methodologies, supported by UMBERTO software and the ecoinvent database, this study compares the environmental impacts of a conventional global semi-automated production process with those of a European fully automated process incorporating robotic sewing technology.

The findings suggest that full automation, when combined with reshoring production closer to the point of sale, can significantly mitigate the environmental impact of a cotton T-shirt's life cycle. This reduction is achieved through decreased transportation emissions and more efficient resource utilization, such as a 15% decrease of current overproduction. Economically, the research explores the viability of investing in automation and relocating production to high-wage countries. Although the initial investment costs for automation are substantial, the study indicates that these could be offset by long-term savings in operational costs, enhanced production efficiency, and reduced dependency on a globalized supply chain.

The study also examines the social implications of fully automated production, such as potential job displacement and the need for workforce retraining in high-wage countries, to mitigate the negative social impacts associated with automation. Additionally, the legal implications and regulatory requirements are critically assessed, particularly in light of new European Union directives, such as the Digital Product Passport (DPP) and other sustainability regulations. These legal frameworks are poised to play a pivotal role in shaping the future of garment production, mandating greater transparency and sustainability.

In conclusion, while the shift to fully automated garment production presents both challenges and opportunities, it has the potential to revolutionize the fashion industry by reducing environmental impact, enhancing economic efficiency, and meeting regulatory demands.

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List of Abbreviations

AWS	Aggregated Weighting Set
AUT	Austria
BG	Bangladesh
CAGR	Compound Annual Growth Rate
CEAP	Circular Economy Action Plan
CFP	Carbon Footprint of a Product
CGT	Cotton Gin Trash
CSRD	Corporate Sustainability Reporting Directive
DE	Deutschland (Germany)
DHU	Defects per Hundred Units
DPP	Digital Product Pass
EOL	End-of-Life
EF	Environmental footprint
ESPR	Ecodesign for Sustainable Products Regulation
EU	European Union
FU	Functional Unit
GHG	Greenhouse Gas Emissions
ILO	International Labour Organization
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
NAFTA	North American Free Trade Agreement
OECD	Organisation for Economic Co-operation and Development
PB	Planetary Boundaries
PCF	Product Carbon Footprint
PEF	Product Environmental Footprint
SAM	Standard Allowed Minutes
SDG	Sustainable Development Goals
SMED	Single Minute Exchange of Dies
TUR	Türkiye
UNCTAD	United Nations Conference for Trade and Development
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
USA	United States of America
USMCA	United States – Mexico – Canada – Agreement
VDI	Verein Deutscher Ingenieure

WRC	Worker Rights Consortium

1 Introduction

This chapter introduces the initial situation, as well as defines the problem which is also the foundation for defining the objective and research questions. After that the methodical procedure of the thesis, as well as the structure of work is described.

1.1 Initial Situation and Problem Definition

For over 200 years, the fashion production process has seen little to no technological innovation or change. However, during this time, consumer requirements and behaviors have shifted dramatically. Today, consumers expect a wide variety of clothing options at low prices. In response to rising production costs, the industry has largely relocated to low-wage countries. In turn, this shift has resulted in several negative consequences, such as high CO2 emissions, long supply chains, and unsocial working conditions.

One potential solution to these challenges is investing in full automation of the production process. However, until now, these investments have not been widely pursued because they are not seen as attractive. This is due to several factors, including a lack of technological know-how, high research and development costs, and low profitability levels.

Nevertheless, as the fashion industry is one of the three most CO2 intensive sectors, and changes in consumer behavior are not in sight, manufacturers are in charge of rethinking their way of production. Moreover, due to several regulations and directives presented and demanded by the EU for more transparency and sustainability in this sector.

1.2 Objective and Research Questions

The objective of this work is to illustrate the life cycle of a cotton T-shirt produced through a semi-automated process and to compare it with a fully automated production process that utilizes robotics for the sewing stage. This comparison aims to analyze both the ecological and economic potential of these two production methods: a fully automated process based in Europe (Scenario B) versus a conventional semi-automated process operating on a global scale (Scenario A). Additionally, the research explores the socioeconomic implications of reshoring to fully automated production in high-wage countries. Thereby, the following three research questions are posed:

- Can full automation and reshoring production closer to the point of sale reduce the environmental impact of a Cotton T-Shirt’s life cyle?
- Does it make sense from an economical perspective to invest in automation and relocate production?
- Which further consequences would a fully automated production additionally imply?

1.3 Methodical Procedure

This work employs a multi-step methodological approach to analyze the fashion production process and the implications of transitioning to a fully automated system. The procedure is structured as follows: First, a comprehensive theoretical background and literature review is conducted to provide a foundational understanding of the current state of fashion production. This review covers various aspects, including the production process itself, legal requirements, shifts in consumer behavior, social implications, and the status quo of current and future technologies for automation. This step ensures a holistic overview of the industry and its challenges, setting the stage for more detailed analysis. Next, a Life Cycle Assessment is performed using the UMBERTO software in combination with the ecoinvent database. This step involves modeling the environmental impacts of a cotton T-shirt across its entire life cycle, from raw material extraction to disposal. The LCA method allows for a detailed comparison of two production scenarios: a conventional semi-automated process and a fully automated process. The results provide insights into the ecological potential and sustainability of each production method. Comparing both life cycles a focus on identifying key differences in terms of resource use, emissions, and overall environmental footprint is the main objective.

Lastly, a Cost-Effectiveness Analysis of the sewing robot is conducted to explore the economic aspects of automation. This analysis evaluates the financial viability of investing in fully automated production, considering factors such as initial capital costs, operational costs, and potential savings from reduced labor expenses. The aim is to assess whether the economic benefits of automation outweigh the costs, particularly in high-wage countries where labor expenses are a significant concern.

Together, these methodological steps shall provide a comprehensive framework for understanding the potential ecological, economic, and social impacts of transitioning to a fully automated fashion production process.

1.4 Structure of the Work

This work is organized into six main chapters, each of which builds upon the previous one to provide a comprehensive analysis of the current and future state of fashion production, with a particular focus on automation and sustainability. Chapter 2 provides a detailed overview of the fashion industry's evolution, from its early days to its current state. It begins by exploring the historical development of fashion, including the globalization of fashion production and the shift towards fast fashion. The chapter then delves into global fashion production and trade dynamics, highlighting key exporters and importers of clothing and providing a deep dive into cotton production. It also addresses the various challenges faced in global fashion production, including emerging dynamics, legal requirements, environmental impact, social implications, and a breakdown of the price components of a T-shirt. Finally, this chapter examines the state of automation in garment manufacturing, covering advancements in textile forming, material spreading, cutting, handling, and sewing.

Chapter 3 lays the theoretical groundwork for the research by introducing two key analytical frameworks: Life Cycle Assessment (LCA) and profitability analysis. The chapter begins with a comprehensive introduction to LCA, explaining its methodology, structure, and different types. It then transitions to profitability analysis discussing both static and dynamic methods of investment analysis. These foundations are crucial for understanding the comparative analysis presented in the subsequent case study.

After that, Chapter 4 implies the practical part of a case study is conducted to compare the life cycle of a cotton T-shirt produced via semi-automated and fully automated processes. The chapter outlines the methodology, defines the goals and scope of the study, and provides a detailed life cycle inventory. It then performs a life cycle impact assessment using IPCC and Environmental Footprint methods. The chapter also interprets the results through a hotspot analysis and comparative analysis of both production scenarios, including a sensitivity analysis and discussion of uncertainties. Finally, an economic perspective is provided, comparing shirt manufacturing in different countries. Chapter 5 summarizes the key findings of the research, highlighting the implications of fully automated garment production and its potential impact on the fashion industry. It also provides an outlook on future trends and potential areas for further research. In the final chapter all the references used throughout the work are compiled, providing a comprehensive list of sources for further reading and verification. Lastly, the appendix includes supplementary materials, such as detailed data tables, additional analyses, and other relevant information that supports the main text of the work.

2 Fashion Production

2.1 The Evolution of Fashion

This chapter evolves the historical development of the fashion production industry. Therefore, the early days of fashion, as well as its transformation to a global production and market shift towards fast fashion are discussed.

2.1.1 The Early Days of Fashion

In previous centuries, clothing was primarily viewed as a necessity, and apparel manufacturing served a functional purpose, resulting in lower complexity related to product characteristics. (According to Brun and Castelli, 2008)

Consequently, until the mid-1980s, the fashion market was relatively uniform. Low-cost mass production of standardized styles without any frequent changes determined the success of the manufacturer. Most fashion industries traditionally launched two collections each year, corresponding to the main seasons (fall–winter, and spring-summer), and also introduced evergreen products or classics that remain on the market for multiple seasons. In those early days, apparel fulfilled basic functional needs, such as protection from the cold or comfort during summer, and consumers were less sensitive to style and fashion, preferring basic apparel (According to Bhardwaj and Fairhurst, 2010).

2.1.2 Globalization of Fashion Production

However, during the last decades, the fashion industry has been redefined significantly. Customers began to not only want to buy clothes as a means to an end but have also been looking for further shopping alternatives beyond traditional retail stores and even personalizing clothing for an affordable price. (According to Jo Anderson-Connell *et al.*, 2002) In turn, the fashion market became highly competitive and the constant need to refresh the product range has inevitably forced many retailers to increase the frequency of new collections and therefore, the number of seasons. (According to Bhardwaj and Fairhurst, 2010)

Reflecting on industrialization, it revolutionized textile production by automating processes like spinning and weaving, thereby reducing labor and fabric costs, and altering the perceived value of textiles. However, sewing resisted automation, unlike spinning and weaving.[1] Thus, two centuries after the Industrial Revolution, sewing in garment factories is still dependent on human labor. Consequently, as demand for clothing increased, lowering labor costs, rather than material costs, was the common approach to offering lower prices to end customers. (According to Houseman, 2023)

[1] More on the topic of automation is discussed in Chapter 2.4

As a result, under the rising trend of globalization, many top brands chose to outsource their production to low-wage countries as a prevalent strategy. Due to competitors' decision to send jobs offshore, lots of additional corporations felt the urge to follow this trend, to remain competitive. (According to Shelton and Wachter, 2005, p. 319). This substantial shift was enabled through several trade agreements, such as the former North American Free Trade Agreement[2] (NAFTA) enacted in 1994. Consequently in the United States (but also in Europe), textile and apparel manufacturers and retailers actively searched globally to find suppliers who can meet the criteria of high quality, low costs, reliable delivery, quick response time, and flexibility. (According to Su *et al.*, 2005, p. 1)

The result was a general shift to mostly Asian low-wage countries, which could match these criteria. Hence, the affordability of garments for European consumers increased.

2.1.3 Market Shift Towards Fast Fashion

The inception of Fast Fashion traces back to the mid-1980s, coinciding with the expansion of the American mass production system, as highlighted by Doeringer and Crean, 2006. Linden, 2016 underscores that the reliance of major retailers on supply chains in developing nations has been influenced by consumer preferences and a growing exposure to increasingly affordable products. Furthermore, the process of industrialization and the rise of wage labor spurred the garment industry. This led to retailers' need to place substantial orders to meet seasonal demand, resulting in large inventories requiring equally large storage space. Consequently, there were instances where consumer demand wasn't accurately understood, leading retailers to resort to end-of-season sales. (According to Doeringer and Crean, 2006).

Previously, consumers often had to pay premium prices to access the latest fashion trends. Today, fast fashion companies have facilitated this access through their efficient production chains. (According to Linden, 2016)

The term Fast Fashion itself began to surface in the late 1990s, describing the swift evolution of fashion trends and the corresponding consumption patterns that some companies have begun to adapt to. (According to Shimamura and Sanches, Maria Celeste de Fátima, 2012) In practice, factors such as production speed, time, and especially the efficient management of risk-related problems have made Fast Fashion producers successful. (According to Cietta, 2012)

Based on Caro and Martínez-de-Albéniz, 2015, p. 7 "*fast fashion can be defined as a business model that combines three elements: quick response, frequent assortment changes, and fashionable design at affordable prices*", whereas the first two elements characterize the operational aspects of a fast-fashion supply chain. Being able to keep up to date with the newest trends, a significant decline in the length of fashion product life cycle is needed, which has in turn increased pressure on retailers to switch products more frequently. (According to Barnes and Lea-Greenwood, 2010) In the meantime, the big players in the fast fashion industry, such as "*Inditex (Zara) and H&M can produce apparel from design to distribution in three to eight weeks*" (Jacobs, 2006). The ecological consequences of that are further explained in Chapter 2.3.

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[2] Since July 1, 2020 replaced by the *United States – Mexico – Canada – Agreement (USMCA)*

2.2 Global Fashion Production and Trade

Today, the fashion industry is bigger than ever before. Although the COVID pandemic has had an impact on profits, the industry has shown its reliance by more than doubling the levels of economic profit in 2022, in comparison with all years from 2010-2022. (According to Amed *et al.*, 2024, p. 10) Already in 2014, due to the growing Fast Fashion Industry, the amount of newly produced clothes per year exceeded 100 billion, equating to a revenue of 1,8 trillion US dollars. (According to Keller *et al.*, 2014)

2.2.1 Exporters of Clothing

Having a closer look at the world exports of clothing from 2000 to 2022, depicted in Figure 1, the following Top 10 regions dominated the market:

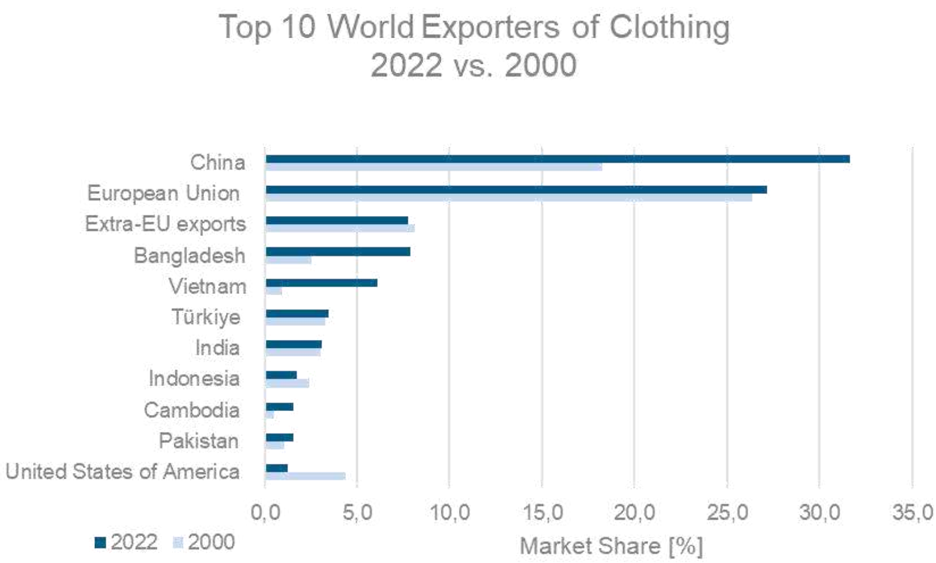

Figure 1: Top 10 World Exporters in Clothing 2022 vs. 2000[3]

According to the data of the World Trade Statistical Review 2023, the above chart shows at first glance that a lot has happened in terms of market dominance and share expansion in the space of around 20 years. While the European Union[4] was still the clear export leader in 2000 with 29.7% compared to China (18.2%), China has managed to increase its share by more than 70% to 31.7% and thus has taken the lead. This was already apparent in 2010 when China recorded its highest market share of 36.9%. Moreover, in addition to China, two other Asian countries have experienced a particular upswing: Vietnam and Bangladesh.

[3] Source: Date from Appendix, World Trade Statistical Review 2023

[4] "Extra-EU" refers to transactions with countries outside the EU, encompassing external trade, balance of payments, foreign direct investment, migration, transport, tourism, and other areas where movements of goods, capital, or people between the EU and the rest of the world are measured.

In the period under review, Vietnam more than tripled its exports from its former ninth place in the world ranking and is now one of the top five exporters of clothing worldwide. Bangladesh is in fourth place with a market share of just under 8% in 2022 and has thus increased its exports 5.6-fold since 2000, the most in percentage terms. (According to Degain *et al.*, 2023, p. 80)

The reason behind the success of Bangladesh are several factors making the country an attractive option for international garment production. These include its large, low-cost labor force, supportive government policies such as tax breaks and subsidies, and strategic location near major markets like India, China, and Southeast Asia. Additionally, Bangladesh's strong export focus to push the country's export revenue, the government's investment in ports and transport networks, and its effort to comply with international standards[5] contribute to its appeal. Finally, the country's growing consumer demand and availability of skilled labor further enhance its attractiveness to international customers seeking to produce garment products in that region. (According to Bappi, 2023)

Another interesting aspect that is not immediately visible in

Figure 1 is that the total market share of all top 10 exporters has risen from 62.8% (2000) to over 85% (2022), which reflects a general concentration of power within the industry. This trend suggests globalization, with major players expanding their international operations and supply chains. Competitive advantages such as efficient production processes, branding, and access to cheaper labor markets likely contribute to their dominance, especially to the power of producing countries in Asia. Changes in supply chain dynamics and strategic partnerships may also play a role in their success. Overall, the rise in market share points out the apparent shifts in the textile and apparel industry toward greater competition, consolidation, and globalization. (According to Degain *et al.*, 2023, p. 80)

Under this rising trend of globalization and the tough battle for the lowest production costs (as shortly described in section 2.1.2), the following chart (see Figure 2) of the percentage distribution of clothing export market shares by world region also highlights the changing emphasis of production sites:

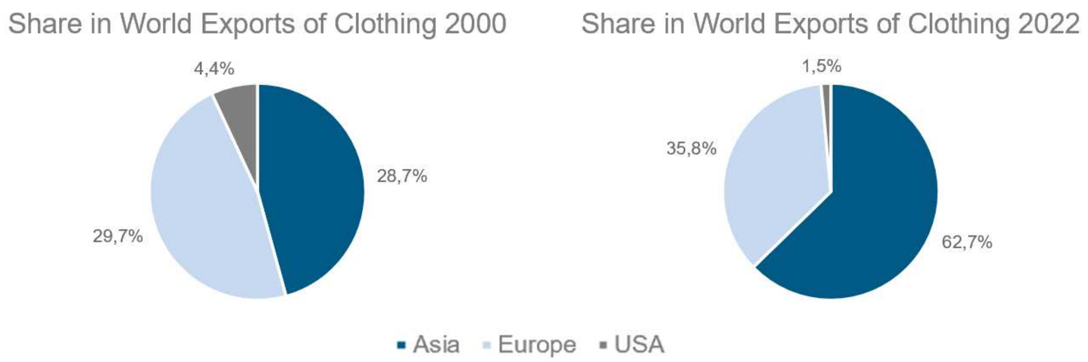

Figure 2: Distribution of Clothing Exports Market Share by Region 2000 vs. 2022[6]

[5] Such as ISO 9001 and SA8000

[6] Source: Date from Appendix, World Trade Statistical Review 2023

Whereas Europe used to be the market leader with 29,7%, followed by Asia with 26,7% market share in world exports in 2000, due to the outsourcing of production, Asia was able to more than double its percentage to 62,7% in 2022. (According to Degain *et al.*, 2023, p. 80)

2.2.2 Importers of Clothing

On the other hand, the clothing import market also changed between 2000 and 2022, as visible below in Figure 3:

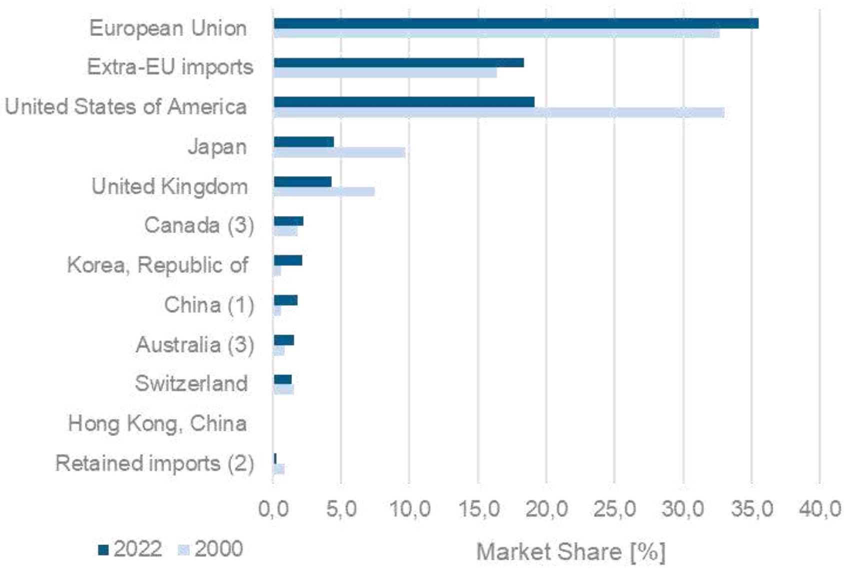

Figure 3: Top 10 World Importers in Clothing 2022 vs. 2000[7]

While the market share of the European Union (EU) (and Europe as a whole) remained almost constant, imports particularly in the USA fell significantly by over 13%. The reason behind that is not only the global COVID pandemic, leaving its marks on the development of the imports. Another crucial factor of influence is shipping delays and supply chain disruptions resulting in unusual seasonal patterns of US apparel imports, already noticeable in 2021. (According to Lu, 2022) Besides that, decelerated economic growth plus the unprecedented high inflation in major apparel import markets, especially in the United States and Western European countries, harmed consumers' available budget for discretionary expenditures, such as clothing purchases. (According to Lu, 2023)

Although the ranking of the Top 10 world importers of clothing did not change in the main, the overall market share dropped from 89,3% (in 2000) to 72,9% (in 2022) showing the diversification of sourcing and the rise of emerging markets with competitive manufacturing capabilities, reducing dependence on traditional suppliers.

[7] Source: Date from Appendix, World Trade Statistical Review 2023

2.2.3 Deep-Dive: Cotton Production

The manufacturing process of clothing starts with the raw material extraction. Hence, fiber production is the starting point of a cloth's life cycle. In general, fibers can be categorized into two groups: natural fibers and man-made fibers (According to Şen, 2008). Cotton is the most important natural fiber crop worldwide, cultivated in four different species in 75 countries all over the world. With its desirable attributes, cotton has enjoyed a longstanding tradition in the clothing sector, valued for its moisture absorption and durability. Consumers continue to favor cotton products for their lightweight and comfortable qualities, encompassing a wide range of items from towels and bed linens to everyday wear like t-shirts, underwear, and socks. (According to Shahbandeh, 2023)

Cotton cultivation typically involves annual planting, although the species naturally had a perennial growth pattern. The crop faces various challenges, including insect pests, drought, salt stress, diseases, weeds, viruses, and heat stress. (According to Jabran and Chauhan, 2020, pp. 1–2) Poor seed germination is also a notable issue in many key cotton-growing regions worldwide. Therefore, the development of genetically modified cotton varieties has been a significant innovation in combating insect pests and weeds. Hence, cotton cultivation has also played a crucial role in enhancing the livelihoods of people in underserved regions, for example, West Africa. (According to Hussein *et al.*, 2005, p. 40)

However, the heavy use of pesticides and insecticides in conventional cotton farming has been criticized by several organizations and declared as harmful to the health, not only of the farmers but also the environment, calling for an increase the organic cotton production, which can cause up to 26% less soil erosion. With a plus of 37% in production within one year from 2019/20 to 2020/21, the market for organic cotton has been growing tremendously. Referring to figures from 2020/21, already 21 countries worldwide grow organic cotton, with India being the leader (38%), followed by Turkey (24%), China (10%), and Kyrgyzstan (9%). However, organic cotton production currently still makes up less than 1,4% of the global cotton production. (According to Textile Exchange, 2022)

Having a closer look at the distribution of producing countries worldwide, the landscape in 2022/2023 looked as follows in Figure 4: Leading Cotton Producing Countries Worldwide in 2022/2023

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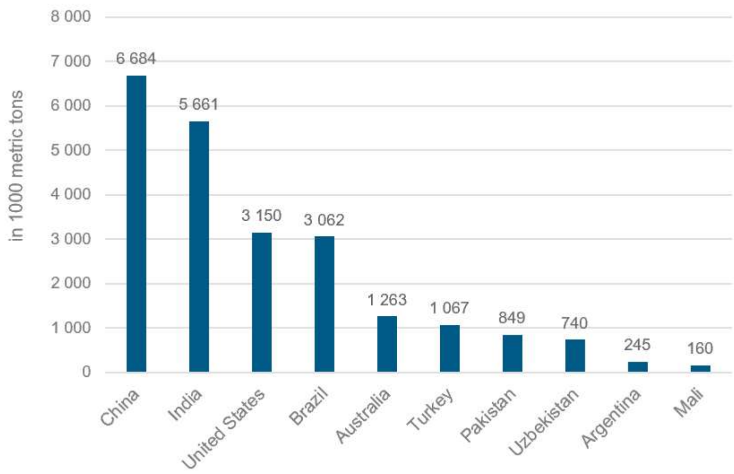

Figure 4: Leading Cotton Producing Countries Worldwide in 2022/2023[8]

As illustrated in Figure 4, China, India, and the United States rank among the top cotton-producing nations in 2022/2023, with the Southern states of the US historically leading in cotton production. This region, once known as the 'Cotton Belt', saw cotton as the primary cash crop from the 18th to the 20th century. However, due to factors such as soil depletion and societal and economic shifts, cotton production has waned, with these lands now predominantly utilized for crops such as corn, soybeans, and wheat. (According to Shahbandeh, 2023) That’s why, in turn, China and India also overtook the U.S. in terms of cotton produced. Another interesting fact visible in Figure 4 is, that Türkiye, ranked 6th place, has the biggest market share of cotton production in Europe. However, it must be noted, that the cotton production in Türkiye experienced a significant unexpected decrease in Kahramanmaras, the center of Türkiye's cotton yarn and textile production, due to earthquakes on February 6th, 2023. (According to Erdogan, 2023)

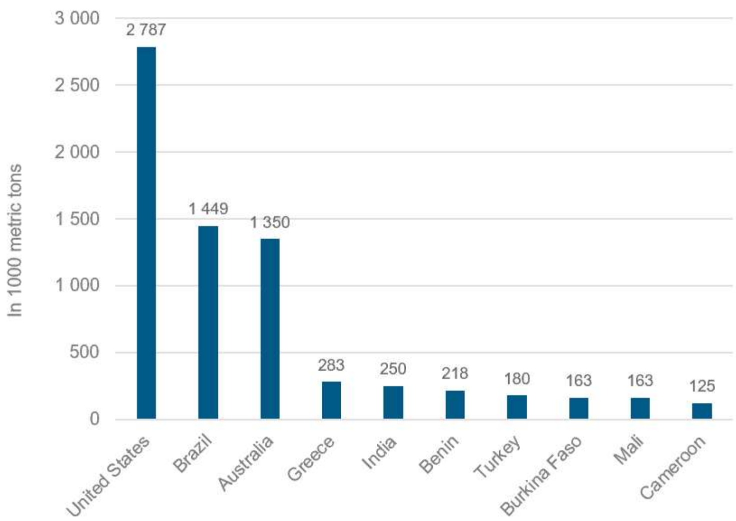

Figure 5: Leading Cotton Exporting Countries in 2022/2023[9]

[8] Source: Foreign Agricultural Service/USDA (2024, p. 17) (slightly modified).

[9] Source: Foreign Agricultural Service/USDA (2024, p. 17) (slightly modified).

Regarding the export numbers for cotton (see Figure 5), the United States of America is the clear market dominator, with a share of around 40% of the Top 10 exporting countries worldwide. From a European perspective, only 6,5% can be attributed to European production – 4% to Greece and 2,5% to Türkiye.

2.3 Challenges in Global Fashion Production

The following section discusses the changes, economic challenges, and legal requirements in the field of global fashion production. It explores the evolving landscape and the multifaceted challenges and requirements shaping the industry. Moreover, it examines the ecological and social consequences of global fashion production.

2.3.1 Emerging Dynamics and Impact

In the highly competitive global market, fashion companies are constantly forced to offer a wider range of products, deliver goods faster, and reduce their costs. For several decades, cost savings have been achieved by lowering operating costs, e.g. reducing labor costs while using advanced manufacturing equipment to improve production efficiency. In recent years, however, the input costs of textile and apparel manufacturers, such as labor, energy, and raw materials, have steadily increased. Even despite migration to the now main producing countries of China, Vietnam, Indonesia, Bangladesh, Burma, and Cambodia, minimum wages, inflation, supply costs, and exchange rates are rising rapidly there, often faster than labor efficiency is increasing. In addition to the growing labor problem, textile manufacturers are faced with a constant increase in raw material costs. The rise in raw cotton and wool prices has increased the demand for alternative man-made fibers. In turn, the increased demand for man-made fibers and rising oil prices have driven up the prices of synthetic fibers such as polyester and nylon. As a result, there is growing pressure to keep the cost of garments low. (According to Nayak and Rajiv, 2018, p. 139)

Fragile supply chains and overall cost increases

The stability of the global textile supply chain is under significant threat due to inflationary pressures tightening their grip. More than any other industry, textiles are highly susceptible to price fluctuations in the global economy. The invasion of Ukraine by Russia occurred just as the global economy was beginning to recover from two years of Covid-related disruptions and adapt to the "new normal". (According to McKeegan, 2022)

Intercontinental supply chains are now struggling to find equilibrium amidst geopolitical disruptions and post-Covid demand surges. The extensive list of disrupted supply chains, with skyrocketing prices, is primarily driven by the petrochemical sector:

Container freight rates, for example, experienced significant fluctuations from January 2023 to March 2024. The rates reached a low point on October 26, 2023, with a 40-foot container fetching only 1,342 U.S. dollars. Subsequently, the global freight rate has generally risen, peaking at over 5,800 U.S. dollars in June 2024, marking the highest value ever recorded. (According to Statista, 2024a) Moreover, the average crude oil price doubled between June 2020 and June 2024. (According to Statista, 2024b)

Besides that, the textile industry felt a significant impact, when cotton prices doubled between 2020, rising from $0.78 in March 2020 to $1.54 in March 2022. (According to

Trading Economics, 2024) Polyester fiber prices also saw substantial increases, with a 48% rise during the same period. (According to US Producer Price Index, 2022)

Further downstream, prices of cotton and polyester fabrics have also risen; for instance, the global cotton price increased by over 30% between 2020 and 2023. (According to FRED, 2024)

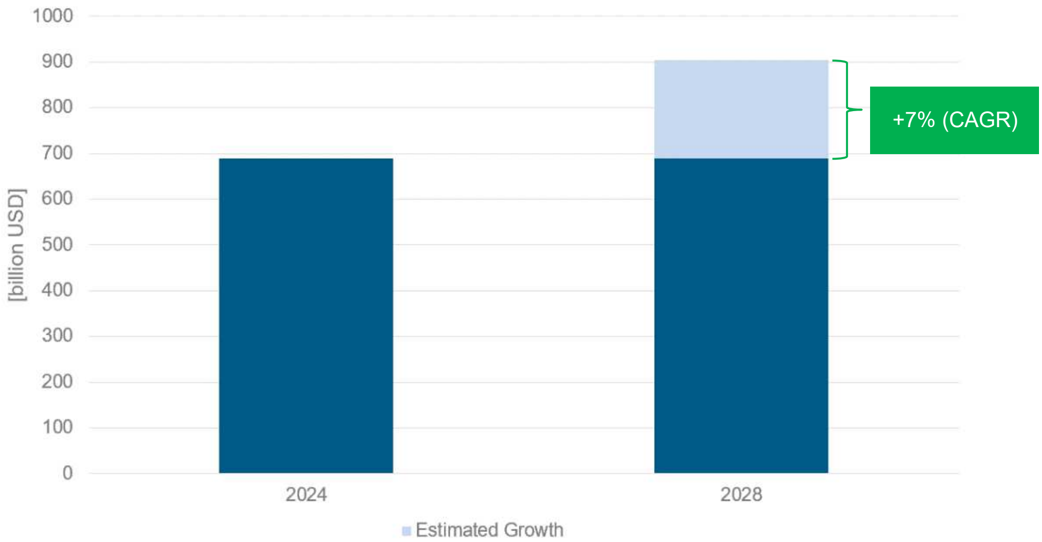

Figure 6: Global Textile Market – Market Forecast 2024-2028[10]

However, as visible in Figure 6, the global textile market size, which has been valued at USD 689,54 billion in 2024, is expected to reach USD 903,45 billion by 2027 – a compound annual growth rate (CAGR) of 7 % and a ~ 30% overall increase within the next four years. (According to Research and Markets, 2024) Therefore, finding innovative solutions to deal with the current dynamics will be critical.

Overproduction and waste of textiles

Because the world's consumers purchase more clothes while wearing them for less than half the time than ever before, nowadays garments get cast away as fast as trends shift. (According to United Nations Environment Programme, 2024) This in turn leads to tons of textile waste. According to a report of Ellen MacArthur Foundation, 2017, p. 37, it is assumed that every second one full garbage truck of textiles is either incinerated or landfilled.

But not only consumer behavior has a big impact on waste. Consumers might not realize that 35% of all materials in the supply chain become waste before reaching them. This waste includes cutting remnants, unusable stock due to last-minute design changes, and spoilage during transport. However, the largest contributor is excess inventory that fails to sell in the retail market. Out of the 150 billion garments produced annually, only 20% to 30% sell at full retail price, and 40% to 50% sell at a discount. The remaining 30% do not sell at all and are sent to landfills or incinerators. (According to Fashion Mannuscript, 2020)

This issue is not only ecological but also detrimental to business. Brands face high risks to their profitability, with the industry losing about $500 billion each year due to unsold

[10] Source: Research and Markets (2024) (slightly modified).

clothes being discarded and a lack of recycling. (According to United Nations Environment Programme, 2019)

On top of that, it is estimated that currently less than 1% of textile waste is recycled into new garment fibers, since neither the infrastructure nor technology can absorb the large volume of garments. Additionally, another difficulty in recycling garments lies in the frequent mixture of different materials, such as cotton and polyester, which complicates the process even more. (According to The Green Side of Pink, 2024)

On the other hand, the primary cause for overproduction is the lengthy apparel development process: Designing, sampling, merchandising, pattern grading, cutting, and sewing are all inefficient and require extensive manual labor and multiple rounds of revisions across teams. Even for large brands, it typically takes three to six months for new products to reach retail stores. To compensate for this long lead time, brands must predict consumer demands months in advance. Predicting fashion demands is incredibly challenging, especially with trends changing rapidly in the age of social media. Many brands use big data and machine learning to analyze consumer behavior, predict trends, and design products. However, the lengthy production time reduces the efficiency of these methods. (According to Fashion Mannuscript, 2020)

Manufacturers also contribute to the problem. Most apparel manufacturers are low-tech and inflexible, relying heavily on manual labor and outdated practices compared to factories in other industries. Without advanced technology, setting up a production line for each new style of garment is time- and resource-consuming. To be cost-effective, manufacturers require a minimum order quantity. Therefore, brands must order large amounts of each design before manufacturers agree to produce, further contributing to overproduction and waste. The cost of excess inventory is twofold. To mitigate losses from unsold products, brands must cut costs elsewhere while keeping retail prices competitively low. (According to Fashion Mannuscript, 2020) This may also explain the declining quality of fast fashion products, which frequently do not last more than five years, and why factory workers in developing countries are often paid well below living wages, as discussed in Chapter 2.3.3.

The overproduction of clothes further leads to an excessive number of disposed textiles, of which globally around 87% are either incinerated or landfilled. For instance, New York City spends over USD 20 million annually on landfilling and incinerating textiles, primarily clothing. Less than 1% of the material used in clothing production is recycled into new garments, including the recycling of post-use clothing and factory offcuts. Some expert interviews and reports suggest that the actual recycling rate could be below 0.1%. (According to Wicker, 2016) This rate is even lower than in industries known for low recycling rates, such as single-use plastic packaging, where the rate is around 2%. (According to Ellen MacArthur Foundation, 2016, p. 27) Only 13% of the total material input is recycled after clothing use, with most of this recycling involving downcycling into lower-value applications like insulation material, wiping cloths, and mattress stuffing. After serving these secondary purposes, the materials are typically discarded, making them challenging to recover. (According to Lu and Hamouda, 2014)

Collection of post-use clothing varies worldwide, and even in regions with high collection rates, most garments are eventually removed from the system. Globally, about 25% of garments are collected for reuse or recycling through various systems.67 There are significant regional disparities in collection rates; for example, Germany collects 75% of discarded garments, whereas collection rates in the US and China range between 10% and 15%. (According to Korolkow, 2016, p. 35; Ellen MacArthur Foundation, 2017, p. 37)

Many countries, especially in Asia and Africa, lack collection infrastructure. This is particularly significant as clothes collected for reuse in high-income countries are predominantly exported to these regions. Although these efforts help extend clothing utilization, most of these garments eventually end up in landfills or are downcycled into lower-value applications. (According to Watson *et al.*, 2016, 121, 156)

Therefore, solutions to deal with the problem of overproduction are needed. A suggested way to do so requires a shift to on-demand production, where garments are made only after a customer's purchase. This approach perfectly balances supply and demand and eliminates unnecessary waste. Tailors and niche fashion brands already use this method, but with the current supply chain setup, on-demand manufacturing is not feasible for the mass market. It is neither cost-effective for producers nor attractive for customers, who would have to wait weeks for their purchases. However, technology can make on-demand production viable. The fashion industry has been slow to adopt new technology, particularly in manufacturing. The latest inventions in fashion tech have been short-lived PR stunts, like color-changing T-shirts or jackets with built-in speakers. Few companies truly focus on solving pressing issues like overproduction. Although not yet mainstream, existing technology can reduce production lead times to mere hours, making on-demand and sustainable production achievable at a fraction of the usual cost. (According to Fashion Mannuscript, 2020)

One critical bottleneck is labor-intensive Garment Manufacturing, which is still done 100% by hand. However, filling the technology gap with automation and robotics of this process could change the industry drastically. More on that is discussed in Chapter 2.4.

Rise of nearshoring and reshoring

During the COVID pandemic in 2020-2023 (According to World Health Organization, 2024), a clear explosion of the frailties of traditional supply chains took place, resulting in significant disruptions across nearly all industries around the globe, as well as the apparel industry. During post-pandemic times, brands and retailers were still struggling to find a balance between cost, time, and quality as they worked to restructure supply chains. (According to AATCC, 2023)

In the meantime, the apparel manufacturing industry has been witnessing a revival of reshoring and nearshoring. Thus, companies are reassessing their sourcing strategies to simplify their supply chains and better adapt to market changes. These strategies provide benefits such as shorter lead times, lower transportation costs, and improved transparency in the supply chain. (According to Marshall, 2023)

According to the definition of Cambridge Dictionary, reshoring refers to "*moving a part of the business that was based in a different country back to its original country*". In terms of the apparel industry, the "*part of the business*" refers to a "*restructuring global production away from developing and emerging economies, towards the high-income countries many lead brands hail from*". (Eisenbraun *et al.*, 2020) The reshoring trend,e.g. also entailed the foundation of the US "Reshoring Initiative" in early 2010, intending to help manufacturers to again enable local production in the United States. (According to Reshoring Initiative) Since then, they supported numerous apparel and textile brands to manufacture (again) in the US. Until 2015, around 10.000 jobs in manufacturing per year were created, while in the decade before 140.000 jobs per year were lost due to offshoring production. (According to Abbasi, 2016)

On the other hand, nearshoring has as well gained prominence, while companies strive to improve their supply chains. (According to Zeraati Foukolaei *et al.*, 2024) Nearshoring is a business strategy that describes the transfer of a company's operations to nearby countries, (According to Martinez, 2023) and/or closer to the point of sale. By locating production closer to consumer markets, a reduction of lead times, importing, and shipping costs are the key factors for brands to pursue nearshoring, while decreasing inventory and the ability to respond faster to trends and reduce overproduction. (According to Magnus and Ibáñez, 2024)

According to surveys done by McKinsey & Company, nearshoring has been one of the top priorities for European and US apparel executives since 2016. However, despite ongoing efforts, according to one of the latest publications of McKinsey & Company, nearshoring has remained flat. While brands are relying less on China, production has primarily moved to other Asian countries, as illustrated in Figure 7:

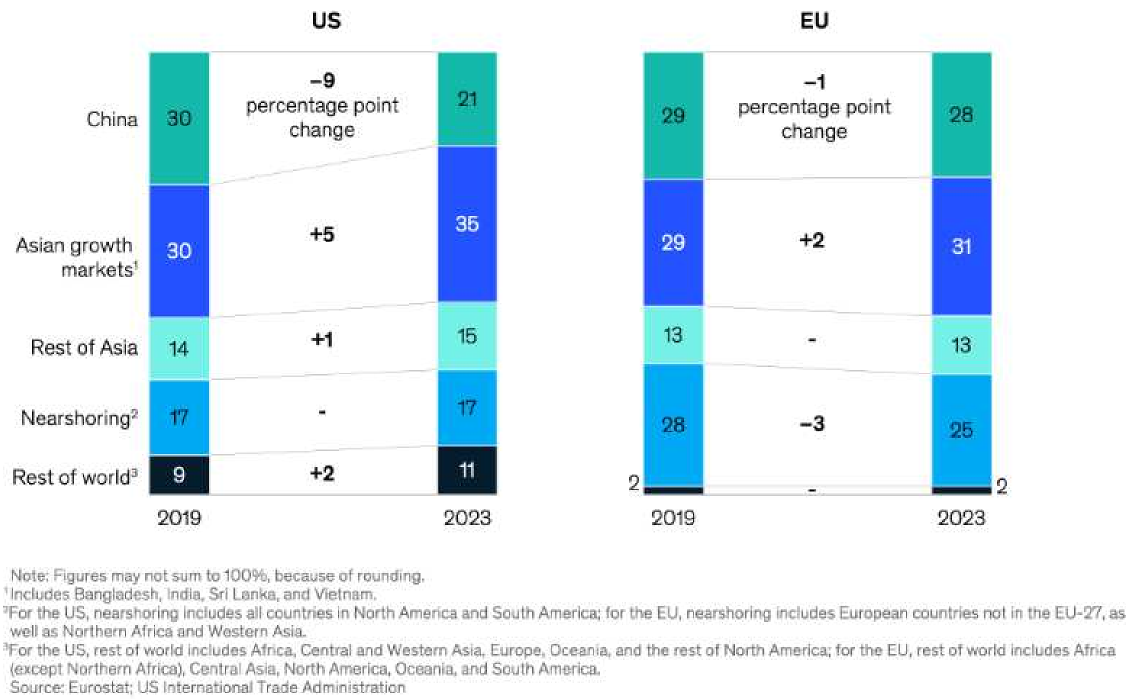

Figure 7: Apparel Imports to EU and US 2019 vs. 2023[11]

Although the advantages of nearshoring are evident, Figure 7 shows, that the proportion of imports to Europe and the United States from countries such as Central America and Mexico has remained relatively unchanged since 2018. According to Magnus and Ibáñez, 2024, this is due to several challenges: Firstly, the total landed cost (the expenses associated with shipping a product) from manufacturers in nearshoring countries to the United States is generally comparable to that of Asian imports; in most cases, the landed cost in these countries is slightly higher despite competitive labor rates, lower shipping costs, and benefits in tariffs and inventory. This discrepancy arises from lower labor productivity in the region and difficulties in procuring yarn and fabric, which are often imported from Asia. Secondly, the supplier bases in nearshoring countries can often produce a more limited range of products.

However, these challenges are anticipated to be addressed in the coming years, since the need to establish integrated supply chains remains. An additional benefit includes

[11] Source: McKinsey & Company (2024).

the reduction of carbon footprint by shortening supply chains and minimizing waste, which is another big challenge the industry faces.

2.3.2 Current and Future Legal Requirements

This section dives deeper into legal requirements concerning the apparel industry. This includes an analysis of global and EU regulatory frameworks and directives, as well as regulations within the EU member states, that influence fashion production practices and strategies.

Decent Work and International Cooperation

Reflecting the necessity for globalization to create jobs of acceptable quality, the International Labour Organization (ILO) introduced the concept of decent work already in 1999. This concept encompasses respect for fundamental workers' rights, adequate social protection, and social dialogue. (According to ILO, 1999) Decent work is also a priority within the United Nations' Sustainable Development Goals (SDG) and was highlighted in the G7 leaders' 2015 declaration advocating for "*responsible supply chains*". (According to G7, 2015, p. 6) Following this, the Organisation for Economic Co-operation and Development (OECD) issued due diligence guidelines for multinational companies in the garment and footwear sector in 2017. These guidelines include detailed recommendations to ensure that fashion companies do not purchase from suppliers who violate workers' rights, such as by forcing excessive hours, compromising health and safety, or denying trade union representation. (According to Organisation for Economic Co-operation and Development, 2018) More broadly, corporate responsibility for protecting human rights was emphasized in the United Nations' 2011 Guiding Principles on Business and Human Rights. (According to United Nations Human Rights, 2011) Decent work is also a focus of EU development cooperation, highlighted in the 2006 and 2017 versions of the Consensus on Development. (European Commission, 2017)

Through the generalized scheme of preferences (GSP), European trade policy facilitates job creation in developing countries. Under GSP, low and lower-middle-income countries benefit from reduced or zero tariffs on exports to European markets, enhancing the competitiveness of clothing and footwear manufactured in these regions. The primary beneficiaries include Bangladesh, Cambodia, and Myanmar, which, as least-developed countries, enjoy zero tariffs. (According to European Commission, 2012) Since joining GSP in 2013, Myanmar's exports have grown significantly, while Bangladesh and Cambodia, long-time participants in GSP, have seen similar benefits. (According to Russell, 2020a)

A condition for zero GSP tariffs is the ratification and implementation of the eight core conventions of the ILO, which restrict child and forced labor, prohibit discrimination, and guarantee the right to form trade unions. Similar conditions are applied to bilateral free trade agreements, such as the one signed with Vietnam in 2019. (According to Russell, 2019b) While these measures do not fully guarantee decent working conditions, they provide the EU with leverage to improve human rights situations. For example, under the "*Everything But Arms*" initiative, a GSP sub-scheme allowing duty-free exports from least-developed countries to Europe, the EU engages in 'enhanced engagement' with nations having serious human and labor rights issues. Thus, Cambodia lost duty-free privileges in August 2020, while Myanmar and Bangladesh remained under scrutiny. since in all three countries, restrictions on trade unions have been a significant concern raised by the EU. (According to Russell, 2019a)

EU Textile Strategy for Sustainability and Circular Textiles

In 2014, the European Commission initiated consultations on an EU garment initiative aimed at regulating or at least guiding supply chains in the fashion industry. In April 2017, the European Parliament expressed its support for this initiative through a resolution.

Meanwhile, the EU has taken significant steps toward reducing carbon emissions and building a more sustainable future. This has been achieved through the implementation of numerous EU regulations and the planned rollout of directives in the coming years. Given the substantial carbon footprint of the textile and fashion industries, they are expected to be highly impacted by these regulations. An overview of the main climate regulations and directives and how they affect textile companies are illustrated in Figure 8. In total, currently there exist more than ten EU regulations or directives, either already in place or the pipeline, that will influence fashion brands based in the EU and abroad.

Figure 8: EU Climate Regulations and Directives[12]

As shown visually in Figure 8, most of the regulations are under the scope of the European Green Deal, which generally aspires to position Europe as the first climate-neutral continent by 2050. To achieve this, it sets forth ambitious environmental goals and targets, forming the basis for a series of directives and regulations that are being continuously introduced. Among its key targets is a substantial reduction in net greenhouse gas emissions, aiming for at least a 55% decrease by 2030 compared to 1990 levels. Additionally, the initiative highlights the importance of reforestation and ecosystem restoration, to plant 3 billion trees across the EU by 2030.

Two specific plans under the European Green Deal are particularly relevant to understanding the current and forthcoming climate legislation. The Circular Economy Action Plan (CEAP) is a pivotal component of the European Green Deal. Consisting of 35 distinct actions, it places particular emphasis on the textiles sector, identified as one of the most resource-intensive industries. The CEAP introduces a series of initiatives

[12] Source: Adapted from Carbonfact (2024).

designed to foster sustainable product design, implement circular economy practices, and reduce waste generation. (According to European Commission, 2024a)

To fulfill the commitments of the European Green Deal and the new CEAP, the EU has crafted a dedicated strategy for the textile sector. The EU Strategy for Sustainable and Circular Textiles aims to transform the entire lifecycle of textile and footwear products, addressing not only how materials are produced but also how they are consumed and ultimately disposed of. This strategy includes measures to extend the lifespan of textiles, increase the use of recycled fibers, discourage fast fashion, and facilitate easier repair or recycling of products through a Digital Product Passport. (According to Carbonfact, 2024)

The following Figure 9 shows a timeline of past and present directives and regulations:

Figure 9: Timeline – EU Directives and Regulations[13]

As visible in Figure 9, several directives and regulations are already in place or currently further developed. A more precise description of the them can be found below.

Waste Framework Directive

Adopted in 2021, the updated directive on waste shipments aims to promote a circular economy and prevent the export of textile waste to developing countries. It facilitates waste transportation and recycling within the EU while enhancing measures to track illegal waste shipments. The concept of Extended Producer Responsibility (EPR) is integral to this directive, holding producers accountable for the entire lifecycle of textile products, from design to disposal and recycling. By January 1, 2025, Member States are required to implement systems for the separate collection of textile waste. Each country will establish its own EPR, and fashion brands will need to participate in an EPR for every country they operate in. (According to European Commission, 2023b)

Ecodesign for Sustainable Products Regulation (ESPR)

Recognizing that product design accounts for 80% of a product's environmental impact, the Ecodesign Directive, previously limited to energy-related products, will expand to include textiles and other sectors. This regulation aims to ensure products are more durable, reliable, reusable, upgradable, repairable, easier to maintain, refurbish, and recycle, and energy and resource efficient. Fashion brands intending to sell in the EU must consider these factors throughout the product lifecycle, ensuring transparency and traceability to enable informed consumer choices based on sustainability. The specific Ecodesign requirements for textiles are expected to be finalized by mid-2025. It has been an approved EU law since June 2024. Additionally, the regulation introduces the Digital Product Passport. (According to Carbonfact, 2024) The DPP itself is designed to

[13] Source: Own Figure

enhance transparency and traceability in the supply chain by providing detailed digital information about products. It aims to support sustainable practices by offering data on a product's environmental impacts, materials, and recycling information. (According to European Commission, 2024a) For the textile industry, the DPP is particularly relevant as it requires to streamline the tracking of garment life cycles, from production to disposal, thereby facilitating more informed decisions on sustainability and circularity. (According to McKinsey & Company, 2022) The introduction of the DPP aligns with broader EU goals to foster a circular economy and reduce waste. (According to Textile Exchange, 2022)

Corporate Sustainability Reporting Directive (CSRD)

The Corporate Sustainability Reporting Directive (CSRD), while not a component of the European Green Deal, aligns with these new regulations as part of the Sustainable Finance Initiative. It mandates that companies assess not only their financial status but also their sustainability practices, which will have significant implications for fashion and textile brands. The directive will require enhanced sustainability reporting, initially targeting large companies with 250 or more employees and all companies listed on the EU market, eventually extending to certain non-EU corporations. These companies must provide detailed disclosures on environmental, social, and governance (ESG) issues, including greenhouse gas emissions, supply chain transparency, labor practices, and diversity initiatives. This heightened scrutiny will compel fashion and textile companies to adopt more sustainable practices.

The CSRD, implemented in 2023, will see its reporting requirements gradually enforced starting in 2024, with reports published in 2025. The EU is developing the European Sustainability Reporting Standards (ESRS), which will serve as the framework for disclosing ESG information.

Green Claims Directive

With numerous environmental labels creating consumer confusion, the Directive on Green Claims addresses misleading and unsupported green claims, as 53% of such claims are vague or false, and 40% lack evidence. (According to European Commission, 2023a) This directive will require that all green claims, such as "*this product has a reduced carbon footprint*," be independently verified and scientifically substantiated, conducting its product environmental footprint (PEF). Additionally, the directive will ensure clear communication of claims, potentially eliminating aggregate scoring of environmental impacts unless allowed by the EU. It seeks to enhance the accuracy of product labels, particularly regarding durability and repairability, by mandating that sustainability claims be backed by third-party reviewed data using standardized life cycle assessment methodologies.

As the European Union progresses with the introduction and refinement of its climate regulations and directives, it becomes increasingly crucial for apparel and textile brands to gain a comprehensive understanding of their product's environmental impact across the entire life cycle. For those in the apparel or footwear industry, it is imperative to prepare for the upcoming EU textile strategy regulations and directives. This preparation is particularly vital as the process of collecting and consolidating all relevant data can be quite extensive and demanding.

2.3.3 Environmental Impact

The fashion industry, a significant component of the global economy, is valued at over USD 2.5 trillion and employs over 75 million individuals worldwide. Moreover, the sector has experienced remarkable growth over the past few decades, doubling clothing production between 2000 and 2014. During this period, consumers purchased 60% more garments in 2014 compared to 2000, yet retained these items for only half as long as they still did in the early 2000s. Thanks to falling costs and the rise of fast fashion, some estimates even claim that "*consumers treat the lowest-price garments as nearly disposable, discarding them after just seven or eight wears*". (McKinsey & Company, 2016, p. 1) This consumer behavior has contributed significantly to the overall fashion industry's CO_2 impact and fostered social inequalities in the sector.

Despite the industry's growth, substantial negative environmental impacts are a growing concern. According to UNEP, 2018, fashion production accounts for nearly 10% of global carbon emissions – more than all maritime shipping and international flights combined. Most of the impact comes from the use of raw materials: Cotton, for example, requires about 2.5% of the world's farmland, whereas synthetic materials, such as polyester, use approximately 342 million barrels of oil per year. Furthermore, 43 million tons of chemicals are required for clothes processing, such as dyeing. (According to Stallard, 2022) Besides that, the industry requires more than 90 trillion liters of water annually, as much as needed to meet the needs of five million people, leading to water scarcity in some regions, (UNCTAD, 2020) contaminates rivers and streams. Additionally, 85% of textiles are discarded annually, and laundering certain garments (e.g. polyester) releases considerable amounts of microplastics into the ocean. (UNECE, 2018)

Breaking the textile consumption down to an average person in the EU, 2020 a total of 400 m² of land, 9 m³ of water, and 319 kg of raw materials was required and caused a carbon footprint of about 270 kilograms, while most of the resource use and emissions took place outside of Europe. The reason for that is, that not only has the production of textiles been shifted to Asia, but also the disposal to low-wage countries, mostly in Africa, through reselling used textiles. This is also notable in the numbers for exports of used textiles in the EU, which have tripled within only two decades – from ~550.000 tons (2000) to almost 1,7 million tons (2019). (According to European Environment Agency, 2023)

The consumption of textiles in Europe exerts considerable environmental and climate-related pressures. A portion of these impacts also arises from the destruction of returned and unsold garments, which are never utilized as originally intended. (see subChapter about Overproduction and waste of textiles) It is estimated that approximately 4-9% of all textile products introduced to the European market are destroyed without fulfilling their intended function. The briefing of the European Environment Agency suggests that the processing and disposal of such returned or unsold items may account for up to 5.6 million tonnes of CO_2-equivalent emissions. This level of emissions is comparable to, albeit slightly less than, Sweden's net emissions in 2021.

2.3.4 Social Implications

When talking about fashion production, social implications play another crucial role. Thus, the following subchapter describes the human costs of fashion, as well as garment workers' conditions.

Human costs of fast fashion

Shifting fashion production from North America and Europe to Asia, developing countries have created jobs and growth, which ultimately lead to a decreased poverty rate. Thus, according to Kim *et al.*, 2006, becoming part of the textile-clothing industry, has been a favorable opportunity for most developing countries to take a step towards industrialization. However, due to the almost unlimited flexibility between countries and factories, manufacturers in developing countries are pressured by European and North American brands by being forced to cut costs to stay competitive. This also highlights the inequalities of the fashion industry created between the global North and South. (According to Russell, 2020b, p. 1)

Therefore, fast fashion's human cost is also significant. Ultimately, it is often the textile workers in factories who suffer, toiling long hours in harsh and sometimes dangerous conditions for wages that barely cover their living costs. (UNEP, 2018; WRI, 2019) The following illustration (Figure 10) shows an illustrative overview of the minimum monthly wages in the textile industry in selected countries as of 2019:

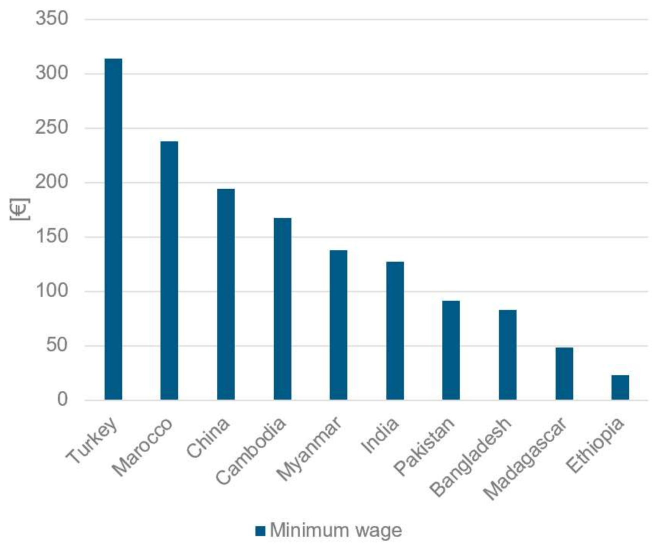

Figure 10: Minimum Monthly Wage in the Textile Industry 2019[14]

Comparing the data collected in 2019 with the figures published in 2017 by The World, makes visible that the monthly minimum wage varies significantly from country to country. But, although customer prices for clothing increased during the last years, there was no clear evidence of a notably higher minimum wage for garment workers, in 2017 and 2019 respectively. (According to Sheng, 2020)

On the other hand, when interpreting the minimum wage level, it must be seen in comparison with the local living wage, since "*a high minimum wage in absolute terms does not always guarantee a high standard of living and vice versa*". (Sheng, 2020) The living wage itself is defined as a theoretical income level that covers essentials such as shelter, water, and food in a specific country. (According to International Labour Organization, 2017) To reinforce the importance of putting minimum wages into perspective of living wages, the graph in Figure 11 shows that e.g. in the United States, garment workers receive one of the highest minimum wages globally at USD

[14] Source: Adapted from Naele and Bienias (2021); Sheng (2020).

1,160/month. However, in 2018-2019, this was only about 70% of the living wage, which was USD 1,660/month. Conversely, garment workers in Indonesia earned a nominal minimum wage of USD 181/month. This amount was significantly higher than the reported living wage of USD 103/month during the same period.

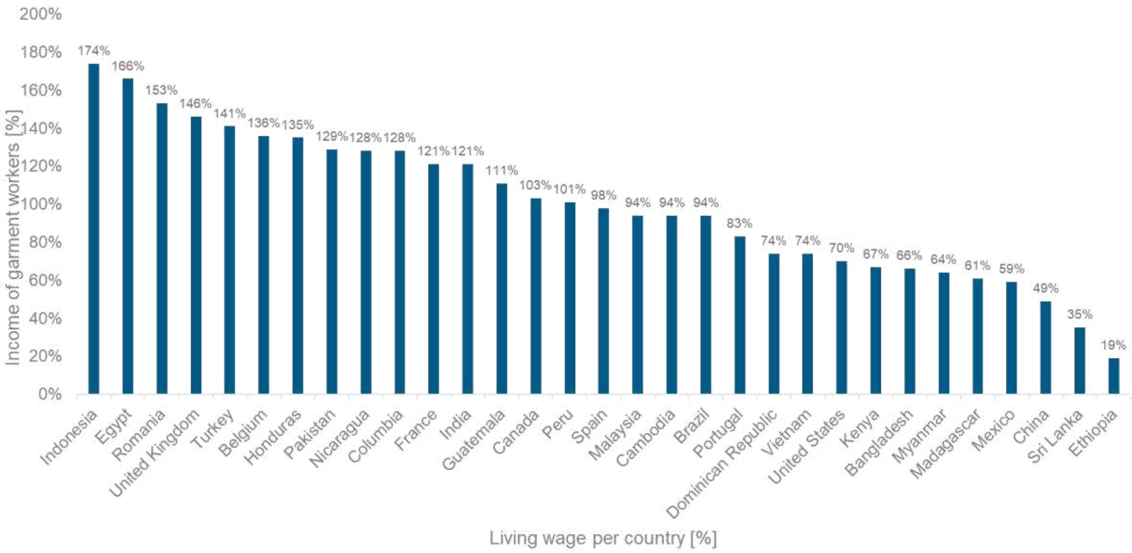

Figure 11: Minimum Wage of Garment Workers as a Percentage of Local Living Wage (2018-2019)[15]

According to several media platforms, lots of protests about minimum wage negotiations in Bangladesh occurred starting from November 2023. Following months of protests, the highly politicized protests have concluded, but experts predict the repercussions will affect the garment industry for years. The Bangladeshi government has established the new monthly minimum wage at 12.500 taka (approximately $113/month), which is just over half of the 23.000 taka (approximately $208/month) proposed by workers and unions when discussions began in April 2023. Besides that, despite inflation and the depreciation of the Bangladeshi taka against the US dollar, the national minimum wage for garment workers has not increased since the last negotiations in 2018, when it was set at 8,300 taka per month (approximately $95 at the time, or $75 today). The trade unions involved in the negotiations have called off the protests to focus on incremental changes within individual factories in the short term. However, they argue that the minimum wage remains insufficient to support a family in Bangladesh, necessitating a long-term solution. (According to Webb, 2024)

The effects of the violent crackdown by the Bangladeshi police and military are still being felt. Throughout the protests, which also began in April and intensified after the proposed increase to 12.500 takas in November, there have been reports of violence against protestors. At least four garment workers have lost their lives, and hundreds have been hospitalized or injured. The advocacy group Worker Rights Consortium (WRC) estimates that between 115 and 200 workers remain imprisoned, many in dire conditions without the possibility of bail. Multiple news sources have reported that between 3.000 and 4.000 workers have been terminated for participating in protests, although WRC has not yet

[15] Source: Adapted from Sheng (2020).

verified these claims. The subdued response from numerous global fashion brands that source their products from Bangladesh has raised significant concerns about the industry's willingness to overlook such issues. (According to Webb, 2024)

According to Cernansky, the brands' purchasing from Bangladeshi manufacturers could actively influence wage negotiations by increasing the payments to factories, thereby ensuring an increase in workers' wages. They can also take substantive actions against the violence faced by workers. However, referring to the Worker Rights Consortium, there have been reports about factories engaging in lockouts and workers being blacklisted, which shows the lack of transparency and thus possible steps for action and supporting garment workers accordingly.

Garment Workers' lives and health risks

Next to too little pay for garment workers, there are several health risks and examples of tragedies due to a lack of security and health standards. In 2013, the collapse of the Rana Plaza building in Dhaka resulted in the deaths of over 1,000 workers and injured 2,500 more from five garment factories – the biggest incident in history. However, this incident is not unique. In 2005, more than 60 Bangladeshi workers died due to the Spectrum factory collapse (According to Clean Clothes Campaign, 2013), and in 2012, a fire at Tazreen Fashions killed over 100 workers. (According to Clean Clothes Campaign) Similar calamities have occurred in India and Pakistan. (According to Kent, 2019) These disasters are largely due to the absence of effective, independent inspections to enforce basic safety protocols. After the Rana Plaza incident, it was discovered that 97% of Bangladeshi factories lacked safe fire exits, 90% were without adequate fire alarms, and 70% had undocumented, potentially unstable extensions. (According to Russell, 2020a) The lack of proper safety measures also means that toxic substances, such as textile dyes, present significant health hazards to workers. (According to Hoskins, 2020)

2.4 Automation of Garment Manufacturing Process

The art of sewing has remained essentially unchanged since the first seamstress applied needle and thread to fabric thousands of years ago. Despite significant advancements in engineering, including mechanized looms and sewing machines, the method of producing sewn goods remains as labor-intensive today as it was a century ago. Adding to this challenge, contemporary consumers demand affordable, high-quality products delivered to their doorstep within days, pushing the limits of the traditional manufacturing model to the brink. (According to Nayak and Rajiv, 2018, p. 179)

In recent decades, manufacturers of sewn goods have reduced costs by relocating operations to developing nations with the lowest wages. However, this approach is becoming increasingly difficult to sustain due to rising labor costs in these countries, a global shortage of skilled workers, and shifts in consumer behavior influenced by fast fashion brands and social media. In accord with that, the importance of innovative automated solutions that enable a reduction in labor costs increased. (According to Nayak and Padhye, 2015)

Some claim that the word "*automation*" is a contraction of the term "*automatic operation*." The origins of automation can be traced back to mechanization, which involves transferring skills and manual activities to machine operation. (According to Gass and Harris, 1996) Manufacturing engineers define automation as a technology that applies mechanical, electronic, and computer-based systems to operate and control production. (According to Jayaprakash and Groover, 2016) Glock has defined three stages in the advancement of sewing technology: Mechanization, Automation, and Robotics. (According to Glock and Kunz, 2005) Robotics, the most advanced form of automation, are computerized, reprogrammable, and multifunctional manipulators designed to move materials, parts, tools, or specialized devices through variable programmed motions to execute a variety of tasks. (According to Rosenberg, 1985).

The following sub-chapter discusses the different levels of automation in the garment manufacturing process.

2.4.1 State of the Art in Textile Forming

Since the advent of mechanical sewing machines in the 1850s, the production of apparel has consistently been and continues to be a labor-intensive endeavor. (According to Abernathy *et al.*, 2006) This characteristic has led the industry to proliferate, particularly in regions with low-wage labor forces. However, these days rising labor costs in emerging countries make it difficult to remain competitive (as described in Chapter 2.3.1).

For years, laser-guided cutting machines and computer-controlled sewing machines have already been in use as valuable automation tools to raise efficiency and lower costs. Especially in the cutting room, the most drastic changes have happened with the help of automation, which is further elaborated in Chapter 2.4.2. (According to Nayak and Rajiv, 2018, p. 163) However, transferring fabric between such machines is still largely done by the human hand, as robots struggle to handle soft fabrics precisely. (According to Kastner, 2022) Therefore, apparel processing still consists of numerous manual-type operations leading to lots of physical and time resources. (According to Mahmood and Kess, 2016, p. 13)

An illustrative overview of the basic process steps in textile forming and its current level of automation is shown below in Figure 12:

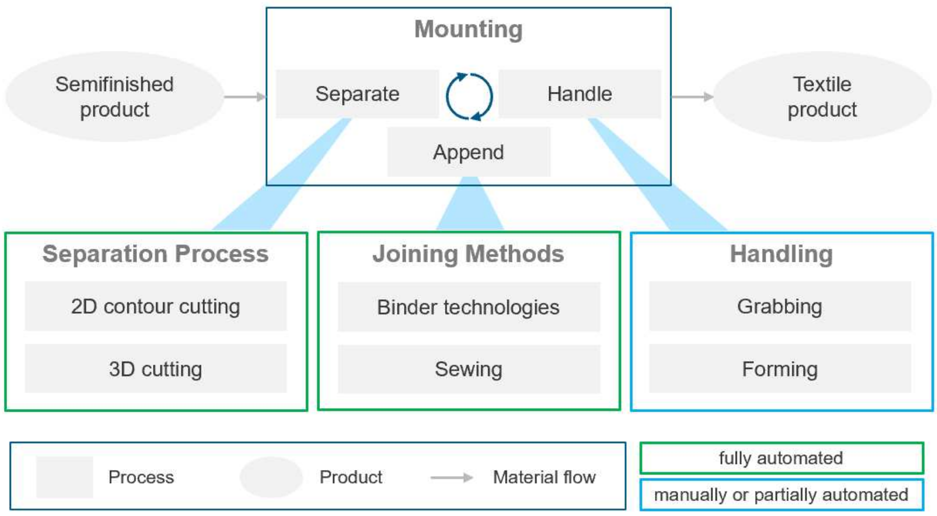

Figure 12: Overview of Basic Process Steps in Textile Forming[16]

[16] Source: Adapted from Nayak and Rajiv (2018, p. 166) (slightly modified)

2.4.2 Automation in Material Spreading and Cutting

Before garments can be sewn, the fabrics must be cut accordingly. For this reason, there is a cutting department, a separate area in a production company. Traditionally, most of the work in the cutting department was carried out by hand. However, the manual laying and cutting equipment and working methods used cannot guarantee high productivity and work quality. When working in the spreading and cutting departments of a production site, employees are exposed to high physical and mental stress, which can harm work efficiency and quality. In contrast to other processes in garment manufacturing, the cutting of garments is highly dependent on the skills, experience, and decisions of the employees in the cutting department. The enormous variety of textile materials, their difference in quality, and the constant pressure to minimize material consumption force the cutting department professionals to work with creativity in every new situation. And that's where automation came into play. With the development of mass production, the invention of a simple spreading machine to move a roll of fabric over the table was the first important. Since then, further technological innovations in spreading and cutting equipment have drastically reduced the human resources importance in the cutting room. It is well known that in many other industries, cutting machines have been used for decades to increase the efficiency and quality of cutting. However, they were limited in terms of flexibility and dealing with frequently changing styles. Consequently, a replacement of die-cut presses was followed by a new type of numerically controlled machine that made a continuous cut using a special cutting device that moved around the profile of the object. At the end of the 1960s, H. Joseph Gerber then invented the first fully automated multi-ply textile cutting system, called the "*Gerber Cutter*".

Today, due to the integration of powerful software, high-tech equipment, and advanced services, the cutting department has emerged as the most advanced sector within an apparel manufacturing enterprise. (According to Nayak and Rajiv, 2018, p. 140)

2.4.3 Automation in Material Handling

As visible in Figure 12, clothing manufacturing can be categorized into two main processes: the joining of fabric components or pattern pieces and the handling of materials. A bulk of the material handling entails the "*transportation of fabrics, cut components, trims, and finished garments from one workstation to the other*" (Nayak and Rajiv, 2018, p. 165). However, even today, a substantial amount of the joining and handling work in both the clothing industry and technical textiles production is done manually, which makes the process highly time-intensive. (According to Nayak and Padhye, 2015)

As per textile researchers at RTWH Aachen University in Germany, the handling time to manufacture one piece of clothing roughly accounts for 80% of all production time (According to Kastner, 2022) Besides that studies showed that handling is responsible for about 80% of the total labor costs. Thus, automation would enable producers to reduce labor costs drastically. But until today there is no fully developed automatic solution on the market. (According to Nayak and Rajiv, 2018, p. 165)

A 2007 published study examining 415 companies from the German automotive, shoe, and protective clothing industries aimed to illustrate the potential for automation. The findings indicated that 85% of the airy body parts were delivered in bales, and 77% were automatically placed and trimmed. Additionally, 79% of the layers were cut as multilayers. However, none of the companies automated the pick-up of the blanks. The joining process handling was 79% manual, and 21% semiautomatic, with 72% of the handling occurring without grippers. The remaining 28% predominantly used needle or scrap grippers. Overall, 59% of the companies conducted a singling process, but none of them were automated. (According to Szimmat, 2007). These results are a strong demonstration of the benefits of automating handling processes in textile manufacturing. It is expected that the results are even lower particularly in garment production due to the higher degree of flexible textiles and the large number of different variants. (According to Nayak and Rajiv, 2018, p. 166)

This also explains the fact, that many brands have chosen to outsource their garment manufacturing process to low(er) wage countries, where they can increase their profits by keeping handling costs much lower than in high-wage countries.

2.4.4 Automation and Robotics in Sewing

Historical developments

Sewing, accounting for 85% of all joining methods (see Figure 12), is the most significant textile joining technology. As a crucial step in the manufacturing process of both clothing and technical textiles, sewing contributes approximately 35% to 40% of the total costs (e.g., for male outerwear), thereby adding substantial value to textile products. The industrialization of clothing manufacturing led to significant changes in work organization and the operational procedures of individual workstations, evolving towards sewing lines and sewing cabins. (According to Nayak and Rajiv, 2018, p. 179)

In the early 1970s and 1980s, extensive research and development efforts were undertaken in the United States, Europe, and Japan, aiming to create a fully automated, flexible, and productive sewing factory devoid of human labor. Significant research and development activities in the sewing sector encompassed technologies for pretreating fabrics to enhance stiffness and pliability, methods for temporarily joining pieces to facilitate efficient sewing assembly, automated sleeve mounting with movable sewing heads, skirt waist belting with movable workstations, spatial clamp systems for shoulder pad sewing, mechanisms for gripping flexible fabrics akin to human handling, and technologies for transporting fabric items between various workstations. (According to Jana, 2003)

Driven by the pursuit of cost reduction, apparel manufacturers gradually embraced automation, since there are several advantages of a higher automation level or robotics: First, robots do not tire and can run, during repair times and maintenance, with constant precision for 24 hours/day. Secondly, they improve the quality and performance of production. Lastly, they are resistant to environmental pollution, such as noise, heat, and dust, which has been a main health concern for garment workers in the apparel industry. (According to Nayak and Rajiv, 2018, pp. 180–181) More on the topic is discussed in Chapter 2.3.3.

As a result, the attempts made in the past to foster automation in the sewing process, enhanced ergonomics, efficiency, and operational safety that can be purchased off-the-shelf or custom-developed by plant engineers or R&D departments. (According to Glock and Kunz, 2000) However, the primary challenge to sewing automation was and still is managing the handling of dimensionally unstable fabrics. Overall, early prototypes of automated sewing systems appeared at machine fairs, but none of these efforts resulted in commercially viable products, (According to Nayak and Rajiv, 2018, p. 199) since aligning two pieces of fabric correctly and feeding them through the sewing head without slippage or buckling, while maintaining proper tension, has proven to be a process better managed by human hands (Reddy, 2016) – at least until 2024.

The Revolution of Fashion Production?

Silana, an Austrian deep-tech startup is currently working on the invention of a robot that fully automates the outdated, manual, and cost-intensive sewing process. This would be the last major processing step in fashion production to be automated. The technological innovation aims to produce clothing sustainably, quickly, and cost-effectively at the place of sale, even in high-wage countries. One sewing robot can replace up to 20 trained seamstresses and thus enable cost savings of up to 85%. This makes it possible for the first time to produce regionally in high-wage countries again and to relocate production from Southeast Asia back to the point of sale. Garments, "*Made in Austria*" at lower prices than "*Made in China*".

According to silana, the 4-times faster production time and significantly shortened delivery routes (-95%) could reduce delivery times from several months to just a few days. Next to enormous economic benefits for fashion retailers producing locally, silana aims to reduce CO_2 emissions by more than a third (38%) and significantly improve working conditions. With a potential market of EUR 63.7 billion and high sales margins, silana could generate enormous profits even with a small market penetration.

Silana is currently already able to produce simple T-Shirts fully automatically with its prototype and has thus shown that fully automated production is possible. Silana has based its technology on state-of-the-art technology and science and has continuously developed it further. At the heart of their innovation is a specially developed gripper, which enables the precise separation, fixing, and further processing of different types of textiles. This allows them to seamlessly integrate additional technologies, which are coordinated by specially developed software and automated and optimized using artificial intelligence. With this combination of advanced technologies and intelligent software architecture, silana wants to enable the design of highly precise and efficient production processes. The next development steps of silana are entirely focused on achieving market readiness with the current prototype. Existing submodules will be revised to increase reliability and a variety of sensors, in particular a specially developed computer vision program, will be integrated for quality assurance during the processing procedure to create a closed-loop system. (According to silana, 2024)

The following case study (see Chapter 4) shall showcase the promised potential of Silanas innovation by conducting an exemplary comparative life cycle assessment with a conventional semi-automated way of production, whose framework and implementation are further explained in the next Chapter 3.1.

3 Theoretical Foundations

This chapter explores key methodologies for assessing the environmental and economic impacts of processes, with a focus on Life Cycle Assessment and profitability analysis. Thus, it provides the theoretical foundation, beginning with an overview of LCA, a comprehensive method for evaluating the environmental aspects and potential impacts associated with a product, process, or service throughout its life cycle. The chapter further details the structure of the LCA method and its various types, highlighting how this approach can be utilized to improve sustainability practices. Following the environmental assessment, the chapter delves into profitability analysis, starting with an introduction to investment analysis. This section discusses both static and dynamic methods used to evaluate the financial viability of investments, providing a balanced view of assessing both environmental and economic dimensions in decision-making processes. Together, these frameworks shall offer a comprehensive foundation for understanding the interplay between sustainability and profitability.

3.1 Life Cycle Assessment (LCA)

In the following subchapter, all aspects of a life cycle assessment are described and discussed. The goal is to understand the concept, the methodology and the different kinds of LCA. Moreover, a detailed description of a whole Products Life Cycle is given.

3.1.1 Introduction to LCA

A Life Cycle Assessment (LCA) is a method for estimating the environmental impact of human activities associated with a product and is based on a life cycle approach. Hence, all environmental impacts accrued from the extraction of raw materials, production, and use to disposal, as well as transport of the product are assessed and evaluated. (According to Frischknecht, 2020, p. 11)

The objective of LCA is multifaceted. It involves quantifying or characterizing all inputs and outputs throughout a product's life cycle, specifying the potential environmental impacts of these material flows, and considering alternative approaches that could improve or mitigate these impacts, (According to Sustainable Facilities Tool) at which the term “product” refers to goods, technologies, and services. (According to Finnveden and Potting, 2014) An exemplary overview of a product’s life cycle including typical categories for inputs and outputs is shown as follows, in Figure 13:

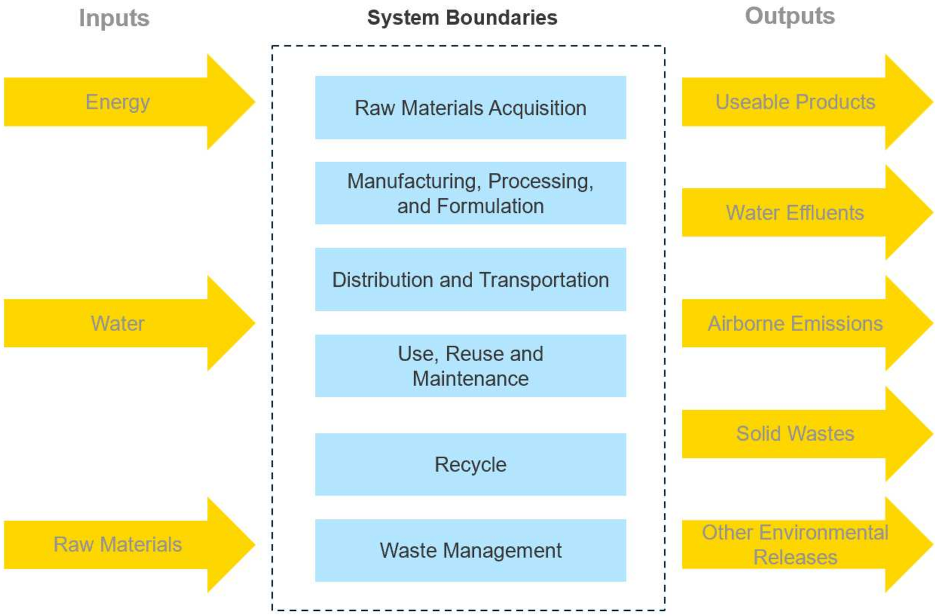

Figure 13: Inputs and Outputs over a Product's Life Cycle[17]

3.1.2 Structure of Method

The International Organization for Standardization (ISO) has defined the procedure within the life cycle assessment method with standard ISO 14040. Referring to ISO 14040, a life cycle assessment is divided into four stages, depicted as follows in Figure 14 and described in more detail in the next sections:

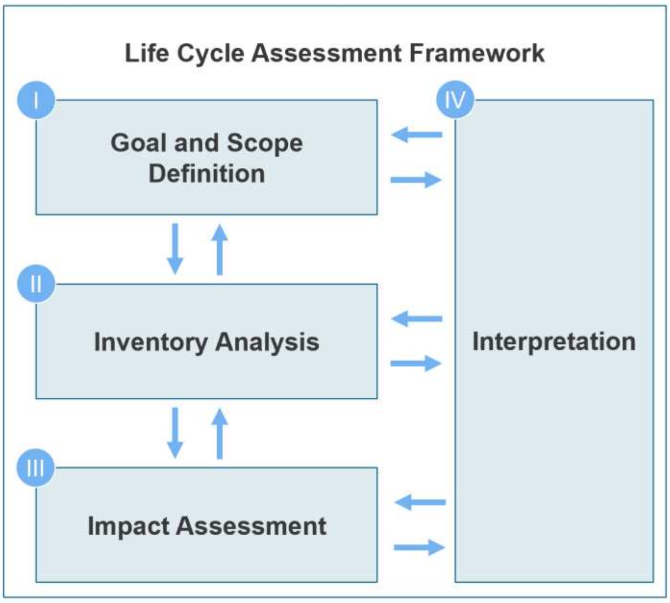

Figure 14: Four Stages of Life Cycle Assessment[18]

[17] Source: https://sftool.gov/plan/400/life-cycle-assessment (slightly modified)

[18]Source: International Organization for Standardization (2006a) (slightly modified)

Goal and Scope Definition

The first step of a Life Cycle Assessment is to set the objectives. Thus, several aspects shall be considered, such as the LCAs' use, the geographical scope of application, and the subject of investigation. For that purpose, the definition of a so-called functional unit (FU) takes place, which is one of the fundamental terms and the centerpiece of an LCA. Depending on the objective, the functional unit serves as a reference and comparison variable. Thus, all environmental impacts caused along the life cycle of a product are related to it. The functional unit must relate to the quantitative benefit of a product or economic activities. Moreover, the definition of the functional unit must contain statements on the required quality of the product or service. The following example shall illustrate the application: Various hand dryers are used in public toilets, such as paper, fabric rolls, hot air, and compressed air devices. The benefit of all these systems is dry hands. Therefore, the functional unit in a life cycle assessment of hand dryers could be "*a pair of dry hands*". For completeness, in the case of consumer goods, user behavior and disposal procedures also need to be considered, when defining the functional unit. (According to Frischknecht, 2020, pp. 28–31)

Due to the high variety and plurality of processes in a product system, many of them might be neglected. Therefore, system boundaries are determined (as already illustrated in Figure 13) To do so, several decision criteria can be pulled. According to the International Organization for Standardization, 2006b, the following three criteria are proposed: mass, energy, and/or environmental relevance. The decision criterion states that inputs that contribute less than a defined proportion of mass, energy, or environmental impact of the total input do not have to be considered further in the LCA. Hence, under the term of cut-off criteria, the product system can be simplified at these points and the parts of the process chains with a low contribution can be cut off. The standard enables the user to determine the threshold value for each case study individually. (According to Frischknecht, 2020, p. 33)

By defining the system boundaries, the whole life cycle stages, either at the beginning or at the end can be left out. The different approaches to do so are further explained in Chapter 3.1.3.

Life Cycle Inventory Analysis (LCI)

The life cycle inventory analysis fulfills the purpose of recording and compiling the environmental impacts and the demand for semi-finished products, auxiliary materials, and energy of the processes involved in the product life cycle. All these processes and their links together form the product system which acts as a network of relations. The data collected during this phase are in turn related to their quantified benefits, the previously defined functional unit. (According to Frischknecht, 2020, p. 11)

This means, that at this stage of the LCA, the product system is broken down into different segments (also known as the life cycle stages), to get data on all environmental influences. Although various approaches to categorize them can be found in the literature, a basic distinction can be made between the following five life stages:

- Raw Material Extraction
- Manufacturing[19]
- Distribution and Transport
- Use and Maintenance
  Disposal and Recycling

Consequently, the preparation of detailed life cycle assessments is data-intensive and requires professional data processing. Simple product systems and rough calculations can be modeled or carried out using spreadsheet programs. However, more complex systems soon reach the limits of manageability and clarity. In addition, the flexibility concerning changes during a project is limited. Therefore, the usage of software is useful and suggested. Meanwhile, there are several programs available, which reduce daily work by a significant amount. (According to Frischknecht, 2020, p. 93) For the aim of the case study of this thesis (read in Chapter 4), the ecoinvent database will be used. (ecoinvent, 2020)

Once the life cycle inventory data for all processes within the scope of the life cycle inventory has been collected, checked, and inserted in the software, the cumulative results can be calculated. For each unit process, the quantity required to produce or provide the functional unit is requested and the associated emissions and resource consumption are added up. This results in long lists of results with cumulative emissions of pollutants into the air, water, and soil and cumulative resource consumption (ores, mineral raw materials, land use, water, primary energy sources), which are not suitable in this form as decision support. Hence, information can be condensed down to one-dimensional values utilizing the subsequent multi-part Life Cycle Impact Assessment. This is explained in the following subchapter. (According to Frischknecht, 2020, p. 96)

Life Cycle Impact Assessment (LCIA)

The Impact Assessment is all about using the data collected through the Inventory Analysis (viz. the results with the cumulative pollutant emissions and resource consumption) and condensing it to only a few (environmental) parameters. Condensing in this context means that the available information is weighted or prioritized. (According to Frischknecht, 2020, p. 101) However, an LCIA does not directly measure a specific impact but merely establishes a connection between a product and its potential consequences. (According to Cotton Incorporated, 2012, p. 8)

An impact assessment is usually conducted using an inherent method of valuation which, if need be, expanded selectively according to the specific needs of a life cycle assessment case study. As already stated in the section *Goal and Scope Definition*, the prioritization as well as the choice of valuation method are to be carried out already at the beginning of a study. This procedure ensures that only further useful data will be collected in the first place and afterward evaluated in the impact assessment. (According to Frischknecht, 2020, p. 101)

In a traditional life cycle assessment, the environmental impacts of products, services, and organizations are quantified. The environmental impacts that (can) be addressed as part of the impact assessment must therefore be determined. The following Table 1 shows an overview of different LCIA methods, including its main characteristics and environmental indicators:

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[19] In practice, the life stage of *Manufacturing* is broken down into several substages, individually depending on the purpose and data availability of the case study

Table 1: LCIA – Overview of Methods

LCIA Method	Main Characteristics	Environmental Indicators	Sources
Eco Indicator 99	Endpoint method focusing on damage to human health, ecosystem quality, and resource depletion. One of the earlier methods for endpoint assessment.	Endpoint indicators: human health (disability-adjusted life years - DALY), ecosystem quality (potentially disappeared fraction of species), resource depletion.	(Goedkoop and Spriensma, 2001)
CML-IA (Institute of Environmental Sciences - Leiden University)	Midpoint-focused method developed by the Institute of Environmental Sciences (CML) at Leiden University. Uses baseline models for impact categories.	Midpoint indicators: global warming potential (GWP), ozone layer depletion, acidification, eutrophication, human toxicity, freshwater toxicity, etc.	(Guinee, 2002)
ReCiPe 2016	Integrates midpoint and endpoint modeling, harmonizes with Eco-Indicator 99 and CML. Supports a wide range of impact categories.	Midpoint indicators: climate change, ozone depletion, acidification, eutrophication, toxicity, resource depletion, etc.	(Huijbregts *et al.*, 2017)
TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts)	Developed by the U.S. Environmental Protection Agency (EPA); primarily used in North America. Focuses on regionally relevant impact categories.	Midpoint indicators: global warming, acidification, eutrophication, smog formation, ozone depletion, human health, ecotoxicity, land use.	(Bare, 2011)
ILCD (International Reference Life Cycle Data System)	Developed by the European Commission to provide a consistent LCIA framework. Balances detail with applicability to a broad range of sectors.	Midpoint indicators: climate change, ozone depletion, human toxicity, acidification, resource depletion, land use, ecotoxicity, etc.	(European Commission. Joint Research Centre., 2018)
IMPACT 2002+	Integrates midpoint and endpoint approaches, linking direct impacts to damage categories. Focuses on human health, ecosystem quality, climate change, and resources.	Midpoint indicators: human toxicity, ecotoxicity, respiratory effects, global warming, ozone depletion, acidification, eutrophication, land use, resource depletion.	(Jolliet *et al.*, 2003)
PEF (Product Environmental Footprint) 3.1	Developed by the European Commission to standardize product-level environmental footprinting, enhances comparability and consistency across products and sectors.	Midpoint indicators: climate change, ozone depletion, acidification, eutrophication, resource use (energy carriers, minerals, metals), water use, ecotoxicity, human toxicity, land use.	(European Commission, 2024b)
IPCC 2021	Developed by the Intergovernmental Panel on Climate Change (IPCC), focuses on climate change-related impacts using the latest scientific data and methodologies.	Midpoint indicators: global warming potential (GWP) over different time horizons (20, 100, 500 years), climate change metrics.	(IPCC, 2021)

When assessing the environmental impact of a product such as a cotton T-shirt, it is crucial to use robust and relevant Life Cycle Impact Assessment methods. Therefore, for the purpose of the case study, conducted in Chapter 4, two different methods are used to assess the environmental impact – the PEF 3.1 and IPCC 2021. Two LCIA methods, that offer significant advantages for such assessments, particularly in the context of evolving European regulations like the Digital Product Passport (see Chapter 2.3.2), which are further explained below.

Product Environmental Footprint (PEF) 3.1

The first method used to assess environmental impacts is the product environmental footprint 3.1. The Product Environmental Footprint (PEF) is one of the LCA methodologies advocated by the European Commission for quantifying the environmental impacts of products and organizations throughout their entire life cycle. The primary objective of PEF is to facilitate the reduction of environmental impacts associated with goods, services, and organizations by considering the entire supply chain, from cradle to grave (More on that in Chapter 3.1.3). This objective is achieved by offering comprehensive guidelines for modeling the environmental impacts of material and energy flows, as well as the emissions and waste streams generated throughout the life cycle of a product or organization. Moreover, the Environmental Footprint (EF) methodologies, encompassing PEF, are periodically revised by the European Commission to maintain a balance between providing a consistent framework and incorporating the latest scientific advancements. The last update, version 3.1, was published in 2023 by Andreasi Bassi *et al.*.

Figure 15 illustrates the procedure of the life cycle impact assessment, conducted with PEF3.1. After successfully collecting relevant data for the life cycle inventory (see Chapter 3.1.2), all inputs and outputs are aggregated in 16 midpoint-characterized impact categories, each one with its unit. After that follows a normalization of the impact categories. This means the results are split by the overall inventory of a reference unit, e.g., the entire world, to convert the before-characterized impact categories into relative impact shares according to the system. Therefore, the same unit “person” is used. Now, weighting factors come into play to reflect the impacts’ perceived relative importance. Thus, points are given to every category. Lastly, the points of the weighted impact categories can then be tot up to obtain the EF single overall score. (According to Andreasi Bassi *et al.*, 2023, p. 5) This score then indicates the environmental impact of a product – the higher the score, the higher the impact.

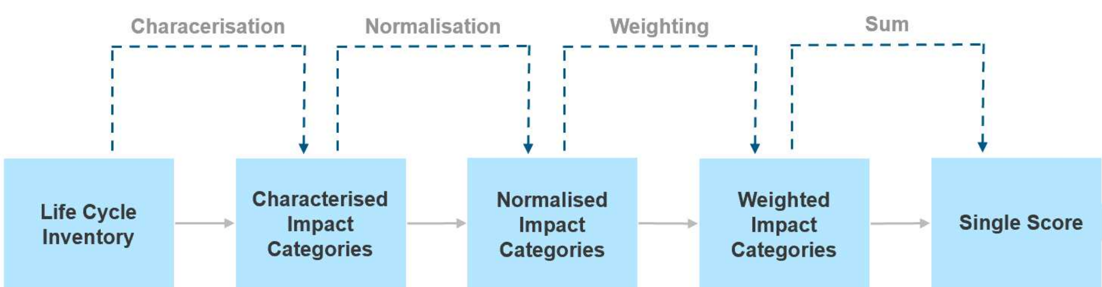

Figure 15: Life cycle Impact Assessment – EF3.1 method[20]

[20] Source: Adapted from Andreasi Bassi *et al.* (2023) (Own Figure)

All 16 midpoint categories including their underlying LCIA method are listed in the following Table 2:

Table 2: Impact categories – EF3.1 method

Impact Category	**Unit**	**Underlying LCIA method**
Global Warming Potential (GWP)	kg CO2 equivalent	(IPCC, 2021)
Climate change	kg CO2 equivalent	(IPCC, 2021)
Abiotic Resource Depletion (ADP)	kg Sb equivalent	(van Oers *et al.*, 2002)
Eutrophication, freshwater (FAETP)	kg P equivalent	(van Zelm *et al.*, 2008)
Eutrophication, terrestrial (EP)	mol N equivalent	(Seppälä *et al.*, 2006)
Eutrophication, marine (MAETP)	kg N equivalent	(van Zelm *et al.*, 2008)
Acidification Potential (AP)	mol H+ equivalent	(Seppälä *et al.*, 2006)
Photochemical Ozone Creation Potential (POCP)	kg NMVOC equivalent	(van Zelm *et al.*, 2008)
Ozone depletion	kg CFC-11 equivalent	(Guinee, 2002)
Ionizing Depletion	kBq U235-equivalent	(Frischknecht *et al.*, 2000)
Human Toxicity (HT), cancer **Human Toxicity (HT), non-cancer**	CTUh CTUh	(Rosenbaum *et al.*, 2008)
Ecotoxicity (ET)	CTUe	
Particulate matter	Diesase incidences	(Peter Fantke *et al.*, 2016)
Water Scarcity Footprint (WSF)	m^3 world eq. deprived water	(Boulay *et al.*, 2018; Frischknecht and Jolliet, 2016)
Land use (LU)	Dimensionless (points)	(Serenella *et al.*, 2018)

IPCC 2021

The second life cycle impact assessment method used is called IPCC, short for "*Intergovernmental Panel on Climate Change*". It has been established on a scientific basis and is regularly updated. The IPCC 2021 follows the latest guidelines to quantify greenhouse gas emissions (GHG), namely the 6^{th} assessment report of the panel. In general, it provides a detailed framework for evaluating global warming. One of the advantages and reasons for choosing this method is, that databases such as ecoinvent come with precalculated aggregated carbon footprints. (According to Stocker *et al.*, 2013)

Interpretation

The Life Cycle Impact Assessment is followed by the last step, the interpretation of the quality of data, to validate the stability of the results obtained in the impact assessment. Sensitivity and uncertainty analysis are conducted to estimate or quantify their uncertainties. Insecurities can occur based on assumptions and decisions made during the previous stages of an LCA and through the gathered data during the inventory analysis or the valuation factors of the valuation methods used. The extreme analysis is a conceptually simple type of uncertainty analysis. By consistently using the minimum and maximum values in comparative life cycle assessments, it is possible to determine whether the ranking of the product variants remains stable even under extreme conditions. However, in practice, this approach is rarely used as it is not implemented in commercial LCA software tools, which makes this type of analysis quite time-consuming. However, a sensitivity analysis is often carried out instead of a systematic extreme analysis. Sensitivity analyses are done to identify decisions and assumptions relevant to the results, to determine their influence on the results, and thus to check the stability of the results. This concerns, for example, the drawing of system boundaries (omission of insignificant processes, omission of entire subsystems such as the administration and research department of a production facility). (According to Frischknecht, 2020, pp. 147–150)

3.1.3 Types of LCA

According to Frischknecht, 2020, p. 164, there exists a range of several types of LCA methods. A first important distinction can be made between consequence-oriented

(consequential) and descriptive (attributional) life cycle assessments. Descriptive LCAs deal with the question of what proportion of an environmental impact is attributable to which products or processes. A consequence-oriented LCA questions what increment, or environmental impact is caused by a decision (e.g. to consume product A instead of product B or to optimize process p).

That means that in a descriptive LCA, theoretically all environmental impacts that can be observed worldwide today are assigned to all products consumed today or the associated satisfaction of all current needs. In contrast, within an impact-oriented LCA, all additional or reduced environmental impacts caused by the additional or reduced satisfaction of a specific need are assigned to this need. This leads to different definitions of the scope of the analysis and different designs of the life cycle inventory and impact assessment models. (According to Heijungs, 1997; Frischknecht, 1998)

Another important distinction of LCAs is concerning the scope of it, which is strongly related to how system boundaries are set. According to the European Environment Agency, an “LCA is commonly referred to as a "cradle-to-grave" analysis, as the LCA is originally based on a whole life cycle approach. This means that the environmental impact of a product is usually recorded and assessed for every single life cycle stage - from the extraction of the raw materials (e.g. cradle), through production and use to the disposal of the product (e.g. grave).

However, based on the available data and the goal of the LCA, it might be reasonable to leave in or take out life cycle phases. Therefore, besides the most comprehensive type of LCA, a *cradle-to-grave* approach, there are two more options for conducting a life cycle assessment and defining its system boundaries: The first option is called *cradle-to-gate*, which evaluates the environmental footprint of a product from the extraction of raw materials to the stage when the product is ready to leave the factory. This approach is valuable for comparing various products' environmental impacts at the production stage. The second alternative that can be used is a *gate-to-gate* LCA, appraising the environmental effects of a product from its entry into the factory gate to its exit. This LCA variant serves to analyze the environmental impact of specific production stages, such as manufacturing, providing valuable insights into the environmental footprint of production processes. (According to Dcycle, 2022) A graphical representation of these options is shown in the following Figure 16:

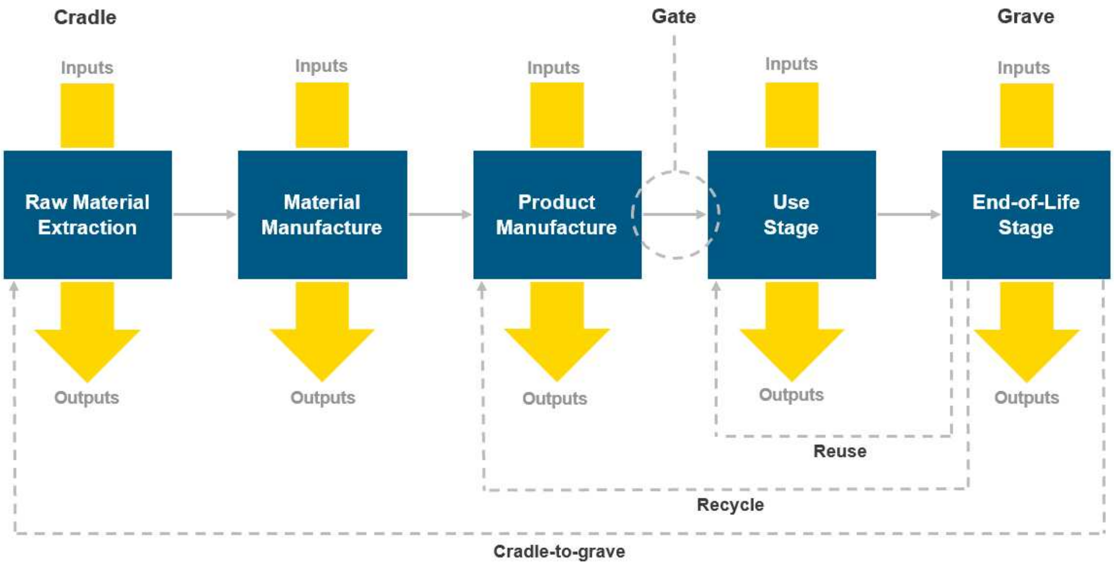

Figure 16: Types of Life Cycle Models[21]

When assessing environmental impacts, the above-shown models of Life Cycle Assessment offer distinct advantages depending on the objectives of the analysis. The Cradle-to-Grave model provides a holistic view of a product's environmental footprint, encompassing all stages from raw material extraction to disposal or recycling. This comprehensive approach is invaluable for developing sustainability strategies, informing product development decisions, and communicating the overall environmental impact to stakeholders. By considering the entire life cycle of a product, organizations can identify areas for improvement and implement targeted measures to reduce environmental harm across all stages of production and use. In contrast, the Cradle-to-Gate model focuses specifically on the manufacturing stage of a product's life cycle. It assesses environmental impacts from the point of raw material acquisition to the moment the product leaves the factory gate. This model is particularly useful for companies looking to optimize manufacturing processes, compare similar products at the point of manufacture, or address environmental concerns related to production activities. Moreover, a Cradle-to-Gate approach may be preferred when data on product usage or end-of-life stages is unavailable or uncertain, allowing organizations to make informed decisions based on the available information. (According to Zamani, 2023)

Nevertheless, in the case of comparing two (or more) LCAs the omission of identical processes is generally permitted. However, this might blur the meaning of comparative graphs, as the relative differences appear larger. Therefore, it is crucial to demonstrate the meaning of these differences in a broader context. (Frischknecht, 2020, p. 187)

3.2 Profitability analysis

Profitability is the most important performance measure used in business operations. Thus it does not imply value, profit maximization is a signification for investment returns,

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[21] Source: Adapted from https://www.paintsforlife.eu/en/product-development/consider-life-cycle

e.g. interest and dividends paid to debtholders and shareholders and growth potential, in terms of retained earnings. (According to Kulwizira Lukanima, 2023, p. 218)

Due to its importance for the case study in Chapter 4, one aspect of profitability, the investment returns, is further elaborated in this chapter. Therefore, it is distinguished between statical and dynamical investment analysis, as well as explained, when and how to use which kind of method.

3.2.1 Introduction to Investment Analysis

The procedures for assessing the profitability of tangible investments are divided into static and dynamic procedures. The classification is based on the aspect that the time of actual payment must be taken into account and that the value of a payment made in the future is lower than the value of an payment of the same amount in the present. Methods that do not take this aspect into are classified as static methods and the other methods as dynamic methods. (According to Becker and Peppmeier, 2022, p. 41)

3.2.2 Static methods

As visible in Figure 17, the static methods of investment appraisal are cost, profit, and profitability analysis. These focus on short-term performance indicators such as profit and costs and are based on averages or a representative period of useful life.

However, static investment appraisal methods have several weaknesses, as they do not, for example, take into account the fact that the underlying data, such as sales volumes or capital commitment, can change over time. Time preferences are not taken into account: An amount of money in a certain period t and the same amount in a later period are considered equivalent and thus consequences of supplementary investments are not captured. Similarly, the financing of the investment is not explicitly taken into account, but only via the calculation of interest rate for the opportunity costs.

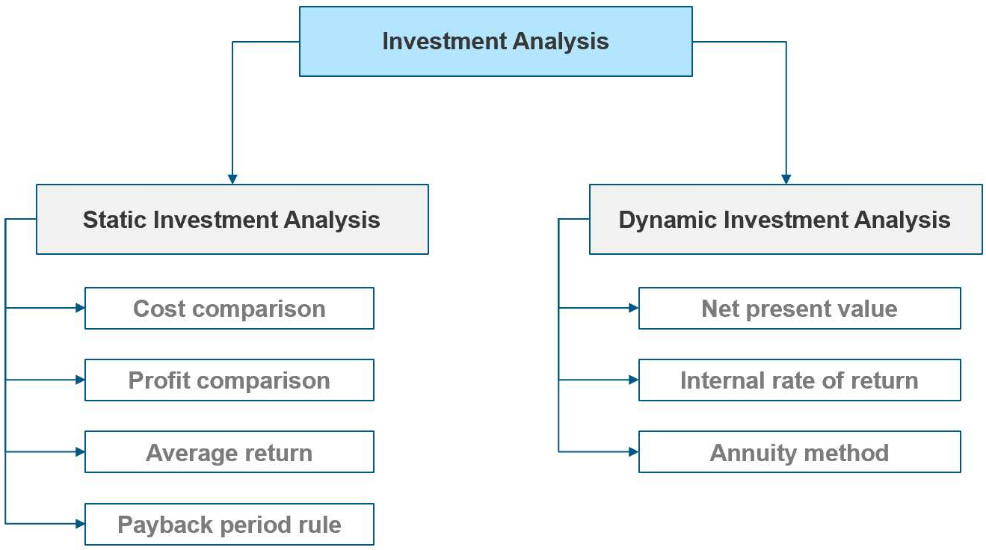

Figure 17: Methods of Investment Analysis[22]

[22] Source: Own Figure

Cost comparison method

By comparing the costs of several investment options, this procedure attempts to determine the one that causes the lowest costs. In principle, all costs caused by the planned investment must be included in the comparison. Revenues are not taken into account, as it is assumed that the amount of revenue remains the same regardless of the chosen investment. The following cost types, which may have to be divided into variable (performance-dependent) and fixed (performance-independent) costs, can be essential for a cost comparison calculation: (According to Becker and Peppmeier, 2022, p. 42)

- Imputed depreciation
- Imputed interest
- Wages and salaries and non-wage labor costs
- Material and energy costs
- Tool costs
- Occupancy costs
- Maintenance and repair costs

Profit comparison method

As a rule, a mere cost comparison is not meaningful for carrying out a benefit analysis. This is particularly the case if the investment objects each generate different revenues. The profit comparison calculation takes this aspect into account. It represents an extension of the cost comparison calculation, as it no longer assumes the same sales prices. It also takes into account the effect of given quality differences in the performance units (e.g. products) that produce the individual investment objects. (According to Becker and Peppmeier, 2022, p. 51)

Average return method

Compared to the cost and profit comparison calculations, a more informative form of the static methods is the profitability comparison calculation. It is used to calculate the profitability of an investment by comparing the annual profit with the capital tied up. The result shows the return on capital employed as a percentage. The investment with the highest profitability is advantageous. As part of the profitability comparison calculation, you can either calculate the net return or the gross return. The net return is calculated by dividing the average annual average profit concerning the average capital tied up capital employed, as in Equation 1. To determine the gross return, the profit is supplemented in the numerator by the imputed interest, as in Equation 2. (According to Becker and Peppmeier, 2022, 53–54)

Equation 1: Net return

$$\text{Net return} = \frac{\text{Profit}}{\text{Tied capital}}$$

Equation 2: Gross return

$$\text{Gross return} = \frac{\text{Profit} + \text{Imputed interest}}{\text{Tied capital}}$$

Payback period rule

The payback period rule determines the period in which the original capital input for investment flows back into the company from future payment surpluses.

investment flows back into the company from future cash surpluses. The capital input corresponds to the acquisition payments, possibly reduced by liquidation proceeds. The cash surpluses result from the difference between cash inflows and cash outflows attributable to the investment under consideration.

The decision rule of this procedure is: The most advantageous object is the one with the shortest amortization period. with the shortest amortization period. When assessing an individual investment, an object is advantageous if the amortization period is shorter than the maximum amortization period assumed by the decision maker. as the maximum permissible amortization period. The main purpose of determining the amortization period is to minimize the risk of capital loss and capital loss and the liquidity effects of an investment. (According to Becker and Peppmeier, 2022, pp. 54–55)

3.2.3 Dynamic methods

The dynamic methods of investment appraisal are characterized by the following features: The averaging approach, on which static methods are based, is abandoned in favor of an exact recording of cash inflows and outflows over the entire useful life of the investments to be assessed. As the cash inflows and outflows may differ in terms of amount and/or timing, comparability is achieved by either discounting the cash flows to the point in time immediately before the start of the investment (point in time zero) or compounding them to the point in time at the end of the investment period.

The following explanations first deal with the basic concepts and the individual dynamic present value method, namely the net present value method, the internal rate of return method internal rate of return method, and the annuity method. Subsequently, the dynamic terminal value methods are then presented.

Net present value method

The net present value (K0) of an investment is determined by discounting the cash inflows (E) and outflows (A) at the individual points in time (t). Discounting is carried out using the appropriate interest rate (i). The discounting interest rate is also called the calculation, capitalization, or comparison interest rate. It represents the interest rate required by the investor.

The net present value K0 is the sum of the present values of all future incoming and outgoing payments less the acquisition payment: The cash flows of an investment can differ in terms of amount and timing. The comparability of the different cash flows is ensured by the fact that they are discounted to their present value. The difference between the sum of the present values of all payment surpluses and the acquisition payment is the net present value of the investment. The net present value does not reflect a period profit, but the total profit of an investment, e.g. the profit that the investment generates over its entire useful life - calculated to the point in time zero, e.g. to the point in time immediately before the start of the investment. Discounting is carried out using a discount rate that corresponds to the required minimum interest rate. A capital value of €0 means that the investment generates exactly the discount rate. The payment surpluses are sufficient to recover the acquisition payment and to earn interest on the tied-up capital at the discount rate. (According to Becker and Peppmeier, 2022, pp. 60–61)

Internal rate of return

The internal rate of return method determines the profitability of the capital tied up in the investment. The internal rate of return method is a variant of the net present value method and looks for the net present value, here the interest rate is sought which leads to a given net present value of € 0.

The decision rule is: An investment is advantageous if the internal rate of return is greater than or equal to the required rate of return. If there are several investment objects to choose from, the one with the highest internal interest rate is preferable.

In the simplest case, there are only two cash flows: a payment at the beginning of the at the beginning of the investment (at time zero) and a later payment. In this case rate (r) is calculated using the following Equation 3: (According to Becker and Peppmeier, 2022, p. 63)

Equation 3: Internal rate of return

$$r = \sqrt{\frac{EZÜ}{A_0}} - 1$$

Annuity method

The method determines the annual surplus available to the investor in addition to capital recovery and interest. It is a purely arithmetical value to be able to represent an arithmetical period surplus. The method is a variant of the net present value method: while the net present value method determines the total return on an investment, the annuity method represents the return for the period. The same criticisms therefore apply to the net present value method. The decision rule is: An investment is advantageous if the annuity is greater than or equal to zero. If there are several investment objects to choose from, the one with the highest annuity is preferable. (According to Becker and Peppmeier, 2022, p. 66)

4 Case Study: Comparative LCA of a Cotton T-Shirt

This case study presents a comparative Life Cycle Assessment (LCA) of a cotton T-shirt, structured to thoroughly analyze the environmental impacts across its life cycle stages. The methodology section outlines the approaches used, including the selection of functional units, system boundaries, and impact categories. Key assumptions, inclusions, and limitations are discussed to clarify the study's scope. The life cycle inventory compiles data sources and process steps, with detailed allocations and calculations provided. The assessment utilizes the IPCC (2021) and Product Environmental Footprint 3.1 methods to evaluate the T-shirt's environmental footprint. Finally, the interpretation section provides insights into the findings and their implications.

4.1 Introduction to Case Study

The fashion production industry is responsible for around 10% of all emissions worldwide. (According to UNEP, 2018) Therefore, the choice of supplier and design of its supply chain plays a crucial role in reducing its ecological impact. Since cotton is the most important and pervasive natural fiber in the world (see Chapter 2.2.3), the investigation of a white cotton T-Shirt is conducted in this case study. Due to the rise of fast fashion, and also its costs, especially for labor, many companies offshored or established their production in Asian countries, as described in Chapter 2.1.2. However, long leading times, overproduction, and social inequalities are the consequences. (More on that in Chapter 2.3.3) Although the level of automation (e.g. the invention of automated sewing and cutting machines) has led to an overall increased efficiency in production, apparel manufacturing is still a highly manual labor-intensive area. (See Chapter 2.3.1) Due to the high complexity of handling materials (fabrics), automation is one opportunity to try solving several issues in the current way of production (as described in Chapter 2.4.4) – including significantly reducing the ecological impact of textiles.

Thus, the current study's purpose is to showcase a comparative life cycle assessment of a Cotton T-Shirt, using two different ways of production – semi-automated globally vs. fully automated European.

4.2 Methodology

This study is based on life cycle assessment (LCA) principles, where all significant processes in the product chain from raw material extraction through production and use to final disposal are included. The LCA is performed according to the ISO 14040 standard and thus consists of four major phases (see Chapter 3.1.2):

- Goal and Scope Definition
- Life Cycle Inventory Analysis (LCI)
- Life Cycle Impact Assessment (LCIA)
- Interpretation and Conclusion

Initially, the goal definition is undertaken to determine the purpose of the study, the specific issues it seeks to address, and the intended audience for the LCA results. This phase sets the context of the LCA study and serves as the foundation for defining its scope. Subsequently, the functions of the product systems and the system boundaries are established. The scope delineates which processes are included in the life cycle assessment and specifies the geographical and temporal boundaries of the system. Additionally, the impact assessment method is selected, with this study utilizing the ReCiPe 2016 and IPCC 2013 (More on the methods can be found in Chapter 0)

Once the context and limits of the study are set, a life cycle inventory (LCI) is conducted to gather information about the physical flows entering (inputs) and leaving (outputs) the system and to develop a corresponding model. Following the LCI, a life cycle impact assessment (LCIA) is performed to evaluate the overall environmental impacts across the defined categories and compare the results of both conducted LCAs. Finally, recommendations and conclusions are drawn based on the contribution of different processes and life cycle stages to the T-Shirt's impacts.

4.3 Goal and Scope of Study

The main goals of this study are the quantification and comparison of the environmental impacts associated with two different product systems, both analyzing a Cotton T-Shirts life cycle. This is done by conducting, analyzing, and comparing two scenarios of producing a T-Shirt, which are further evaluated below in Table 3.

4.3.1 Scenario Definition

For the purposes of the case study two scenarios are assessed, as seen in Table 3:

Table 3: Case Study – Scenario A vs. Scenario B

		Description
Scenario A	Conventional Semi-Automated Global Production	The first LCA is an example of conventional global production of a 100% Cotton T-Shirt, including all relevant transport between process stages. The raw material extraction is assumed to be done in the USA, whereas Shirt Manufacturing is done fully semi-automated in Bangladesh. The retail, use, and disposal phases take place within Germany.
Scenario B	Fully Automated Production in Europe	The second LCA shows a potential way of producing the same 100% Cotton T-Shirt fully automated in Europe, which implies that already the Raw Materials are sourced from Europe (Türkiye), as well as the production, retail, use, and disposal phases take place within Europe.

Thus, a comparative approach is used, to highlight the impacts that are created when raw material extraction in Europe is introduced and when the conventionally semi-automated, and therefore labor-intense, sewing process in Asia is replaced by the fully automated process through a sewing robot in Europe.

More details about the process steps and their geographical scope of application are defined in Chapter 4.4.2.

4.3.2 Functional Unit

In both compared systems, the functional unit of the two product systems is “the use of one medium-sized white 100% Cotton T-Shirt”. Its specific weight is 200 g, which should represent a medium-sized T-Shirt, including a service life of 44 washes, before disposing of it. Laundry care between the wearing phases serves to maintain the value and refresh the worn textile.

Depending on the product system, for production, losses of cotton occur during the ginning, yarn-, fabric, and garment manufacturing stages. This means, that the requirements of cotton in its developing form vary from process step to step. Therefore, most of the LCI data collected is attuned to the amount needed per 1 kg of cotton, to easily measure the different ecological impact, when adapting the amount of cotton needed to produce one T-Shirt. Thus, the unit used for cotton in its developing form is also “kilogram” and adjusted to “pcs”, as soon as the whole manufacturing process is completed, and the T-Shirt becomes a finished product.

4.3.3 System Boundaries

To ensure a full picture of the environmental impacts of both product systems, a cradle-to-grave approach is used for conducting the LCA. This implies a contemplation of every single process stage, thus over a T-shirt’s full life cycle from raw material extraction to disposal.

Regarding the system boundaries of both systems (Scenario A and Scenario B), either share common system boundaries in the retail, use, and disposal phases, while they differ in the raw material extraction, shirt manufacturing, and transport phases, as illustrated in Figure 18 and described below:

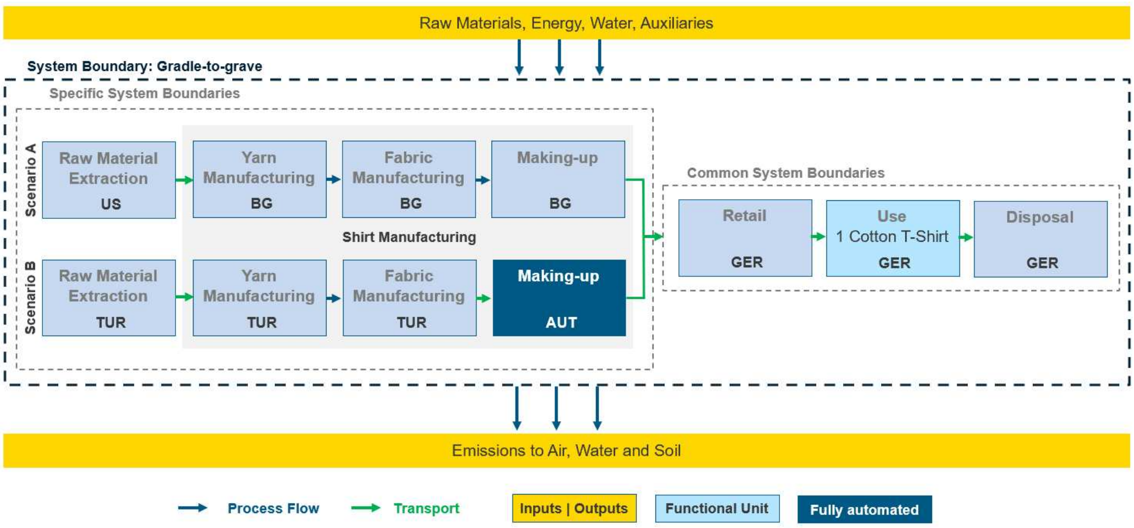

Figure 18: LCA System Boundaries and Functional Unit of Product Systems A and B[23]

[23] Source: Own Figure

Common System Boundaries

As visible in Figure 18, both product systems converge in the following life cycle stages:

- **Retail Phase –** This phase encompasses the process of selling one Cotton T-Shirt to a customer in Germany, including the transportation to the store and the customer. Additionally, a differentiation between online and in-store purchases, and different modes of transport is done. (According to Handelsdaten, 2024) However, it must be noted that energy use within retail environments is neglected.

- **Use Phase –** The use phase entails the consumer's activities related to the T-shirt, such as washing and drying, although mechanical drying is assumed to be used only for 10% after all washes. The number of washes depends on one's customers' behavior, which has a significant effect on the overall environmental impact. Therefore, it is a variant parameter and is elaborated on in more detail in the next Chapter. Since it is not compulsory to iron a Cotton T-Shirt, the process step of Ironing is excluded in this study.

- **Disposal Phase –** This phase includes the end-of-life processes of the Cotton T-Shirt. Thus, the disposal methods of Landfill, Incineration, and Downcycling, are all done in Germany. It must be stated that Recycling was excluded from this study on purpose since less than 1% of all clothes are currently recycled and therefore can be neglected. (According to Press, 2022)

Specific System Boundaries

Next to common system boundaries, there are also unique aspects of the two product systems. The differences can be attributed either to their geographical area of application (e.g. for Raw Material Extraction) or to the way of production, like the execution of the Sewing process - e.g. semi-automated vs. fully automated (as highlighted in dark blue in Figure 18):

- **Raw Material Extraction –** This phase entails the two process steps Cotton Cultivation and Ginning, as well as the transportation between the two facilities. In the conventional production process, all process steps within that phase are done in Texas, USA, since it is known as the leading U.S. cotton-producing state. (According to Economic Research Service, 2024) On the other hand, the cultivation of European cotton is allocated to Turkey, which takes the leading role among the European-producing countries. (See Figure 4)

- **Shirt Manufacturing –** The inherent distinction between the product systems lies in the Making-up process, specifically in how the T-Shirt is sewn. The Yarn- and Fabric manufacturing steps are carried out equally in technical terms in both product systems. However, there exists a difference in regards to the production location: In the global model, production takes place in Bangladesh, the most up-and-coming country in the apparel industry in recent decades (as described in Chapter 2.2.1), whereas the European production (as for Raw Material Extraction) is based in Turkey. Though, the Making-up of the conventional LCA is executed semi-automated in Bangladesh. At the same time, full automation through the aid of a robot is used to shift the process of (Cutting and) Sewing to Austria, before the T-Shirt gets distributed to Germany.

- **Transport –** Conventional production entails a global supply chain, as well as global transportation, which involves shipping raw materials, as well as (semi-) finished products across long distances. For that purpose, in the baseline model, all overseas transportation is considered to be done via container shipping. For the rest of all transports, in both models, a lorry is chosen.

A more detailed visualization and description of all process steps within the product systems can be found in Chapter 4.4.1, illustrated in Figure 19 and Figure 20.

4.3.4 Assumptions, Inclusions and Limitations

Since in some cases, available or aligned data can hardly be found, some assumptions have been made. These assumptions are partially also further challenged in a Sensitivity Analysis, whose results are presented and analyzed in Chapter 4.6.4.

- **Weight of T-Shirt –** The weight of the T-Shirt, the functional unit of this study, is chosen based on an assumption as well as on several other studies, which have used 200 g to conduct their LCAs for analyzing the ecological impact.

- **Losses of Material –** Throughout some process steps during raw material cultivation, as well as shirt manufacturing, losses of materials occur. This happens for two reasons: Either the release of a by-product (see Chapter 4.4.3) or a waste, which cannot be used for further processing. An overview of all losses assumed for the baseline scenario is listed in Table 5. The derivate finally required amount of cotton for producing one T-shirt can be found in the LCI data tables in the Appendix.

- **Overproduction –** Next to losses occurring during several life stages, overproduction is another crucial factor, needed to be considered, when assessing the impact of using one T-Shirt. Thus, in the base line scenario A, a factor of 1,3 is used, which reflects the conventional production. For scenario B, a factor of 1,15 is utilized, since production closer to the point of sale shortens the lead-time and overall improves predictions on the needed amount of T-Shirts. The influence of this parameter is furthermore challenged in the Sensitivity Analysis, which can be found in Chapter 4.6.4.

- **Distances for Transport –** As none of the studies used to carry out the LCA contains an exact location for the process step, all locations and therefore also the transportation distances between them are chosen because of assumptions. These assumptions in turn relate to the core regions of production sites for the respective process steps.

Besides that, a summary of all inclusions and limitations made for the LCA is shown in Table 4. The inclusion or exclusion from the study is based on their relevance to the environmental profiles or the availability of secondary data:

Table 4: Case Study – Inclusions and Limitations

Included in study	Excluded in study
- Cotton cultivation and ginning	- Human labor
- Energy and emissions for yarn- and fabric production	- Production and transport of packaging materials
- Energy and materials for garment production (cut-and-sew)	- Maintenance and operation of support equipment
- Washing and (Mechanical) Drying (including wear and tear of washing machine and dryer)	- Machinery wear and tear (used for Cotton Cultivation and Shirt Manufacturing)
- Auxiliaries use (chemicals, dyes, ...)	- Recycling as a method of disposal
- Transport of intermediate and finished products	- Oil consumption while Shirt Manufacturing
- Transport of finished fabric for cut-and-sew	
- Weight losses of intermediate cotton products	

As visible in Table 4, the wear and tear of machinery is only partially included, such as for a washing machine and dryer, but not for machinery used during Cotton Cultivation or Shirt Manufacturing. The reason behind this decision is, that the wear and tear of the manufacturing machinery can be neglected due to its low impact when breaking the use down to the production of one single T-Shirt, assuming that the life span of one machine is at least 5 years and the production of several 10000 T-Shirts annually.

The weight losses occurring during the Raw Material Extraction and the Shirt Manufacturing Stage for both scenarios respectively, are further elaborated in Table 5:

Table 5: Losses of Material – Raw Material Extraction and Shirt Manufacturing

	Losses of material	
Process Step	Scenario A	Scenario B
Ginning	10% (Cotton Gin Trash) 54% (Cottonseeds, By-product)	10% (Cotton Gin Trash) 51% (Cottonseeds, By-product)
Spinning	5% (Yarn, Waste) 15% (Cotton comber noil, by-product)	5% (Yarn, Waste) 15% (Cotton comber noil, by-product)
Knitting	10%	10%
Dyeing	2%	2%
Cutting	12,5%	10,5%
Sewing	12,5%	3,125%

The biggest differences in the losses occur in the Making-up phase, for Cutting and Sewing. The reasoning behind this lies in the more precise way of manufacturing through automation.

4.3.5 Cut-off Criteria

To ensure that all significant environmental impacts are represented in the study the following cut-off criteria are used:

- **Mass –** If the flow contributes less than 1% of the cumulative mass of all the inputs and outputs of the LCI, it is excluded, provided its environmental relevance is not a concern.

- **Energy –** If the flow contributes less than 1% of the cumulative energy of all the inputs and outputs of the LCI, it is excluded, provided its environmental relevance is not a concern.

- **Environmental relevance –** If the flow meets the above criteria for exclusion yet might have a potentially significant environmental impact, it is reevaluated based on available data and/or assumptions. If the result for an excluded material shows a significant contribution to the overall LCIA, more information is collected and evaluated in the system.

These criteria are also used to justify the excluded elements, which are listed in Table 15.

4.3.6 Impact Categories

In order to quantify the environmental impact, several impact categories are used, such as the midpoint indicators from the EF3.1 method. The framework itself is explained in Chapter 3.1.2, the results for each category can be found in Chapter 4.5. More precisely, the following factors are considered: Climate change, was selected as a first criteria. This factor is of considerable public and institutional interest, and recognized as one of the main factors illustrating the most urgent environmental challenges of our time. The global warming potential impact category is evaluated using the current IPCC characterization factors from the 6th Assessment Report (IPCC, 2021) over a 100-year timeframe (GWP100), which is the most widely adopted metric at present. Eutrophication, acidification, and photochemical ozone creation potentials are chosen because of their strong connections to air, soil, and water quality, and their ability to reflect the environmental impacts of commonly regulated emissions such as NOx, SO_2, VOC, among others. Ozone depletion potential is included due to its substantial political importance, which has led to the global prohibition of the most potent ozone-depleting substances. The phase-out of less potent substances is scheduled for completion by 2030. Current exceptions to this ban exist for the use of ozone-depleting chemicals in nuclear fuel production. This indicator is therefore included for the sake of completeness. (According to Cotton Incorporated, 2016, p. 20)

Furthermore, the project evaluates human toxicity and ecotoxicity potentials, since especially in the shirt manufacturing process, the use of chemicals is potentially harmful to the health of humans. According to United Nations, 2022, approximately two billion people worldwide lack access to improved drinking water, leading to a range of issues related to ecosystem quality, health, and nutrition. Therefore, water consumption, defined as the anthropogenic removal of water from its watershed through mechanisms such as shipment, evaporation, or evapotranspiration, along with the water scarcity footprint (WSF), are also selected as impact factors due to its significant political relevance.

An overview of all impact categories evaluated, including their abbreviations, are listed in Table 6:

Table 6: Case Study – Overview of Impact Categories[24]

Impact Category	Abbreviation	Unit
Global Warming Potential	GWP	kg CO2 equivalent
Climate change	CC	kg CO2 equivalent
Abiotic Resource Depletion	ADP	kg Sb equivalent
Eutrophication, freshwater	FAETP	kg P equivalent
Eutrophication, terrestrial	EP	mol N equivalent
Eutrophication, marine	MAETP	kg N equivalent
Acidification Potential	AP	mol H+ equivalent
Photochemical Ozone Creation Potential	POCP	kg NMVOC equivalent
Ionizing Depletion	IO	kBq U235-equivalent
Human Toxicity	HT	CTUh
Ecotoxicity	ET	CTUe
Water Scarcity Footprint	WSF	m^3 world eq. deprived water
Land use	LU	Dimensionless (points)
Minerals and metals	MM	kg Sb-equivalent
Fossils	FO	MJ

4.4 Life Cycle Inventory

The following Chapter entails the data sources used for conducting the LCA, as well as a detailed description and visualization of all process steps involved in the T-Shirts life cycle.

4.4.1 Data Sources

All data for the product systems inputs and outputs used in this study are mostly referred from publicly available sources, such as previously conducted LCA or directly from industry references, as well as information from confidential sources. In order to calculate the inputs and outputs' environmental impact, the processes are modeled in UMBERTO, while mapping the used data with the ecoinvent database.

[24] Source: Adapted from Cotton Incorporated (2016, p. 21)

Modeling Tools

The modeling of the product systems is carried out using UMBERTO software. UMBERTO is a robust tool for creating and analyzing life cycle models. It allows for the integration of data from various sources, including ecoinvent, to build comprehensive models of the product life cycle. The specific version of the UMBERTO used in this study is, "Umberto 11”, The combination of UMBERTO and ecoinvent data provides a reliable foundation for assessing the environmental impacts of the T-shirt production systems under study.

Ecoinvent Database

The ecoinvent database is utilized as the primary source for life cycle inventory (LCI) data in this study. Ecoinvent provides comprehensive and reliable data on the Global Warming Potential (GWP) for various industrial processes, which is essential for conducting a thorough and accurate LCA. The database includes information on raw material extraction, energy use, transportation, emissions, and waste management, among other processes.

The use of ecoinvent data ensures consistency and comparability of results, as it is widely recognized and used in the LCA community. The specific version of the ecoinvent database used in this study is, "ecoinvent version 3.9.1”, which includes the latest updates and expansions relevant to the production processes being analyzed.

A summary of all mappings of the entries for inputs/outputs in this study to the corresponding data entries in the ecoinvent database can be found in the Appendix, in Table 38 and Table 39.

If there have not been any corresponding data entries in the ecoinvent database available, assumptions for its GWP, so its kg CO_2 per unit, are made, based on secondary data. These values, including their calculations can be found in Chapter 4.4.4.

4.4.2 Process Steps

This section provides a description and the corresponding modeling of every process step in each life cycle stage. The two scenarios contain mostly the same process steps except the omitted “ironing” step and the additional Transport of Cotton Fiber between “Wet Processing” and “Making Up” in the fully automated process. For that reason, the following Figures, Figure 19 and Figure 20, show an overview of all process steps, for both scenarios respectively:

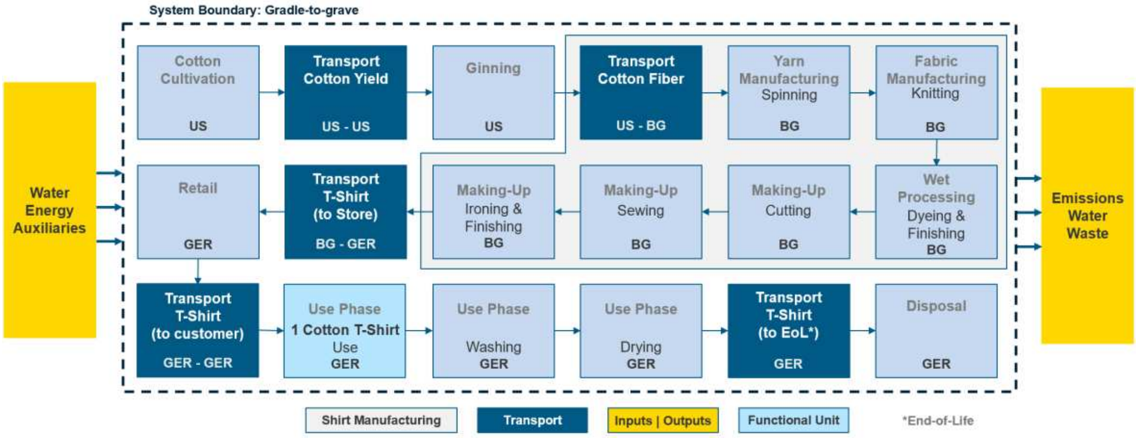

Figure 19: Process Flow – Conventional Global Production (Scenario A)[25]

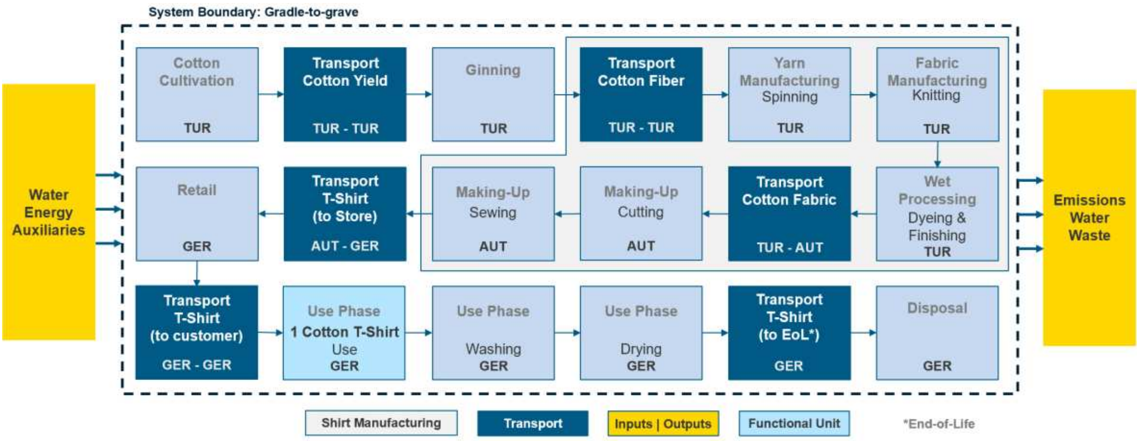

Figure 20: Process Flow – Fully automated European Production (Scenario B)[26]

The process steps, depicted in Figure 19 and Figure 20, are described below.

Raw Material Extraction

The first phase of a Cotton T-Shirts lifecycle is the Raw Material Extraction. It ultimately begins with the Cotton Cultivation, more precisely the cultivation of seed-cotton. Since cotton is cultivated under different geographical and climatic conditions, the specific amount of seed-cotton needed depends on the average yield per hectare, which very much differs from country to country, but also within regions. To achieve a rather higher yield, cultivation often includes a large consumption of artificial fertilizer, water, and pesticides against insect attacks, diseases, worms, and weeds. Although some regions still pick by hand, it is common to use defoliating agents so that the process can be done mechanically. (According to Laursen *et al.*, 2007, pp. 42–43) This procedure is also assumed for this study and the calculations for the required amount of seed cotton, under the assumed yield per hectare, can be found in the Appendix.

After harvesting, the process step of Ginning is carried out, the separation process between cotton fiber and cottonseeds & cotton gin trash (CGT). Since cottonseeds are

[25] Source: Own Figure

[26] Source: Own Figure

one valuable by-product generated during cotton production, an allocation is needed due to its shared environmental burden. This is further elaborated in Chapter 4.4.3. Contrariwise, the cotton fiber is used for subsequent processing in the next life cycle stages.

Shirt Manufacturing

Shirt manufacturing is divided into several process steps: Spinning, Knitting, Dyeing, Finishing, and Making-up. At first, after the extraction of cotton fiber, the process of Spinning is needed to get cotton yarn, which is then further proceeded into the fabric (Knitting) From that point, the Dyeing & Finishing is carried out, which also entails the coloring of the T-Shirt. It should be noted that the coloration of cotton can be done differently – either through dyeing the yarn or the fabric. According to 游志高, less than 10% of the global cotton textiles are yarn-dyed, since they lead to higher production costs and higher technical complexity. Therefore, this study is conducted based on a fabric-dying approach. This case study's last and most important step is the Making-up phase, consisting of Cutting, Sewing, and Ironing. In both scenarios, A & B (see Chapter 4.3), it is assumed that the cutting process is done fully automated with a laser cutting machine. However, both scenarios differ regarding the Sewing and Ironing: For scenario A, the global semi-automated production, the sewing is done manually. Thus, the electricity use of the sewing machines is included in calculating the environmental impact. For scenario B, the fully automated European production, the energy use implies the electricity use of an automated process done by silana, the Austrian deep-tech startup, that has invented the first fully automated solution worldwide.

For the LCA of the Yarn- and Garment Manufacturing (Making-Up) phase, solely energy use (input) and material losses (output) are considered. The maintenance of the machines as well as the making of them are cut off due to their minimal impact on the production of one T-Shirt. All data for the shirt manufacturing process steps are obtained from publicly available secondary data, as well as confidential sources from silana.

Retail

The retail phase consists of one step, the retail itself, which defines the purchase of one T-Shirt. The purchase is either done by the customer himself (on-site purchase) or via delivery service by the brand (online purchase). In order to include all options available, a percentage share of five different modes of transportation for both cases is respected. The values used are based on the in-depth study from Lehmann *et al.*, 2019. However, since the COVID-pandemic in 2022-2023 had a significant impact on the ratio between in-store and online purchases, the relation was adapted to newer studies about customer behavior, according to Handelsdaten, 2024.

Use Phase

The duration of the use phase highly depends on the customer's behavior, e.g. how often the T-Shirt is used, washed, and dried before it gets disposed of. Thus, this phase consists of three steps: Washing, Drying, and Use. Since it is assumed that only 10% of all drying is done mechanically, this step is broken down to all washes done. For reasons of simplicity, it is further assumed that every T-Shirt is washed after one-time use. Since the average amount of uses often doesn’t correspond with the actual lifetime of a T-Shirt, the environmental impact of this phase can differ significantly depending on the individual. For the base scenarios, an amount of 44 washes are used. Several cases are challenged to quantify its influence. (see Chapter 4.6.4) Next to electricity, water, and detergent use, also the wear and tear of a washing machine and dryer for the use of one T-Shirt is considered. Furthermore, it must be noted, that the washing machine utilized by German users is on average only half filled, e.g. 3,5 kg loaded while the maximum loading capacity is 7,5 kg. This has a relevant influence on its ecological impact. The calculations can be found in the Appendix.

Disposal

After clothing has been used, nearly all the value embedded in the materials is lost. Of the total clothes sold in Germany, nearly 90% end up in landfill or incineration. Thus globally, every second, one garbage truck worth of textiles is either landfilled or incinerated. (According to Ellen MacArthur Foundation, 2017, p. 36)

As already stated in Chapter 2.3.3, less than 1% of the material used in clothing production is recycled into new garments, including the recycling of post-use clothing and factory offcuts. There are expert- and report-based assumptions, that the actual recycling rate could be even below 0,1%. In Germany, only 11% of the total material input is recycled after clothing use, with most of this recycling involving downcycling, into lower-value applications like insulation material, wiping cloths, and mattress stuffing. After serving these secondary purposes, the materials are typically discarded. Therefore, this study investigates three options of disposal: landfill, incineration, and downcycling – while “recycling” is neglected.

Transport

In the scope of this LCA, the movement of cotton, in whatever form, is considered. This includes the transport from raw cotton to ginning facilities, as well as transport within the shirt manufacturing stage, distribution, and transport to disposal. For local transport, the use of a lorry, for international transport containerships are chosen – both in combination with emissions factors from ecoinvent. The emissions and resource use associated with transport are calculated per stage and integrated into the overall LCA model. The locations for every life cycle phase are selected based on global industry hotspots. The distances in between can be seen as average including a 10% surcharge for any deviations or last mile distances.

All sources, used for the inputs/outputs of the cradle-to-grave process steps are included in the Appendix. If used for the Sensitivity Analysis, they additionally can be found in Chapter 4.6.4.

4.4.3 Allocations

Within both scenarios of that study, allocations need to be done, since there are two by-products, that are generated within the processing of cotton. The first by-product is cottonseeds, which make up for the majority of outputs during Ginning stage. The second by-product is cotton comber noil which is generated during the yarn manufacturing stage, as described in more detail below.

By-product: Cottonseeds

Each cotton fruit consists of longer seed hairs, cotton fibers, and short seed hairs called cotton linters. When the cotton fruit is ginned, the cotton fibers are detached from the hairy seeds. The long fibers can be spun into yarn and therefore also further used for producing a T-Shirt. Consequently, the ginning process is a coupled process that produces cotton fiber and hairy seeds as well as production waste, known as Cotton Gin Trash (CGT).

Since the hairy seeds and production waste are not required for yarn production, the emissions of processing 1 kg of cotton fruit are to be allocated to the products cotton fiber, hairy seed, and CGT. According to Egbuta *et al.*, 2017, the percentage of cottonseed usually is around 55%. Moreover, up to 10% of each bale of cotton ginned can be assigned to CGT. (According to Egbuta *et al.*, 2019)

The life cycle assessment of both, CGT and cottonseeds plays no further role in the present balance sheet and can therefore be neglected.

By-product: Cotton comber noil

A further allocation needs to be considered for cotton spinning. Cotton fibers, which are used in that stage consist of not only cotton lint but also cotton comber noil. Therefore, during the stage of yarn manufacturing not all of the cotton fiber is transformed into cotton yarn, but also an allocation for comber noil is needed. As a by-product of the combed yarn spinning process, they are mainly reused in the production of nonwoven fabrics, open-end yarns, hygiene, healthcare, and paper products. The percentage of noil can differ within a range from 8-25%, but the most common rate lies between 14-17%. (According to Better Cotton Initiative, 2020, p. 11) Based on those numbers, it is assumed that around 15% of cotton fiber is allocated to cotton comber noil and another 5% are allocated to cotton yarn waste, as visible in the LCI in Table 32 (Scenario A) and Table 34 (Scenario B).

4.4.4 Calculations

As already mentioned in Chapter 4.3.4, several assumptions to determine the LCI data are made. This section gives a more detailed overview of all extra calculations made, such as for the GWP of a washing machine as well as a mechanical dryer.

CO_2 emissions of washing machine

The calculation of the direct emissions for the use of a washing machine per wash cycle are calculated as follows, shown in Table 7, including the according sources.

Table 7: Calculation – Direct emissions of a washing machine per cycle

	Value	**Unit**	**Sources**
Energy consumption	0,7	kWh/cycle	(Lehmann *et al.*, p. 29)
Duration of one washing cycle	2,1	h	
CO_2 Emissions per kWh	0,350	kg CO2/kWh	(*Agorameter*, 2023)
CO_2 Emissions per wash cycle	**0,515**	**kg CO2**	

CO_2 emissions of mechanical dryer

The calculation of the direct emissions for the use of a washing machine per wash cycle are calculated as follows, shown in Table 8, including the according sources.

Table 8: Calculation – Direct emissions of a mechanical dryer per cycle

	Value	Unit	Sources
Energy consumption	0,7	kWh/cycle	(Lehmann *et al.*, p. 29)
Duration of one drying cycle	2,1	h	
CO_2 Emissions per kWh	0,350	kg CO2/kWh	(*Agorameter*, 2023)
CO_2 Emissions per wash cycle	**0,872**	**kg CO_2**	

4.5 Life Cycle Impact Assessment

This chapter entails the results of the impact assessment (e.g. environmental impact and resource consumption) of the life cycle of a standard cotton T-shirt manufactured in different countries, imported, used and disposed of in Germany. The results relate to the life cycle stages and associated sub-process steps, illustrated in Figure 19 and Figure 20. To showcase a broad picture of both scenarios' impacts, two methodologies are used, such as IPCC (2021) and Environmental Footprint 3.1, both methods explained further. The reason behind the decision of choosing these two is their relevance and recognition by the EU.The used impact categories can be found in Table 6.

4.5.1 IPCC (2021)

Running the base line scenario model entailing the LCI data (see Appendix), both scenarios A and B, using the IPCC 2021 method, leads to the following global warming potential, numerically in Table 9 and graphically illustrated in Figure 21:

Table 9: LCIA – GWP for base line scenarios A and B (IPCC 2021)

Life Cycle stage	Scenario A	Scenario B
Raw Material Extraction	0,283	0,217
Shirt Manufacturing	3,612	0,973
Distribution	0,481	0,407
Use Phase	3,533	3,533
Disposal	0,317	0,222
Total impact	**8,180 kg CO2-Eq/Shirt**	**5,351 kg CO2-Eq/Shirt**

Breaking the results down to all process steps within different life cycle stages, the following results, seen in Figure 21, emerge:

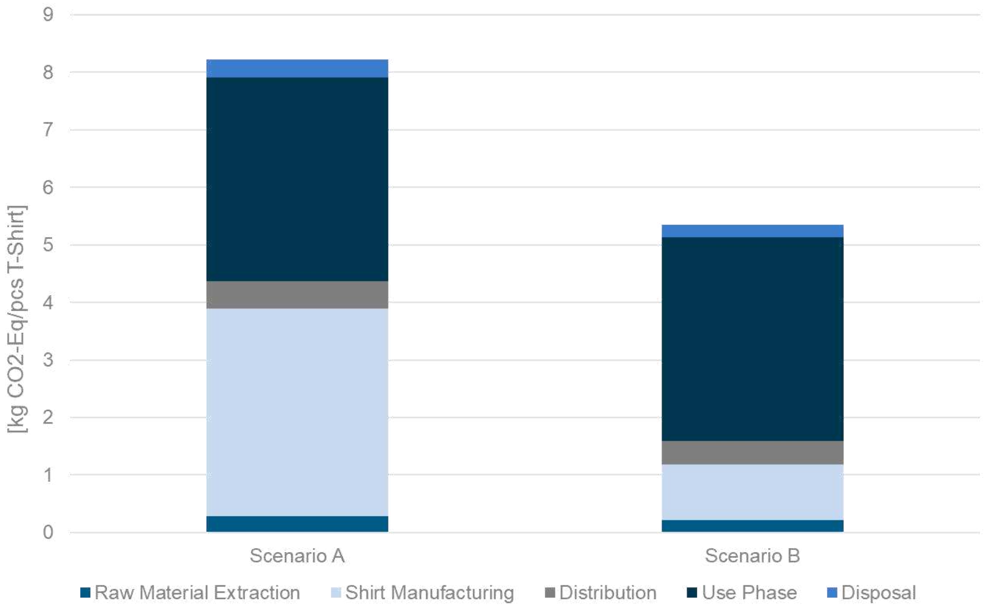

Figure 21: LCIA – GWP for Base Line Scenario A and B (IPCC 2021)

Table 10: LCIA – GWP for process steps in scenario A and B (IPCC 2021)

Life Cycle stage	Process step	Scenario A	Scenario B
Raw Material Extraction	Cotton Cultivation	0,193	0,161
	Transport Cotton, yield	0,018	0,057
	Ginning	0,026	Nearly 0
Shirt Manufacturing	Transport Cotton, fiber	0,195	Nearly 0
	Spinning	0,059	0,014
	Knitting	0,071	0,031
	Dyeing	2,905	0,844
	Cutting	0,078	0,041
	Sewing	0,087	0,042
	Ironing & Finishing	0,216	-
Distribution	Transport T-Shirt (to Store)	0,109	0,035
	Transport T-Shirt (to Customer)	0,372	0,372
Use Phase	Washing	1,239	1,239
	Drying	2,294	2,294
Disposal	Transport T-Shirt (to EoL)	0,107	0,107
	Disposal, T-Shirt	0,209	0,114
Total impact		**8,180 kg CO2-Eq/Shirt**	**5,351 kg CO2-Eq/Shirt**

4.5.2 Product Environmental Footprint 3.1

The assessment, using the Environmental Footprint 3.1 methodology, provides a more in-depth evaluation of the environmental impact. It is especially insightful, because it is a framework aligned with the “Green Claim Directive” of the European Union (see Figure 8). One method of getting results for this method is to assess the impact based on the weighting concept of planetary boundaries (PB), which showcases the effects of humans concerning critical system processes. The PB method identifies critical environmental limits that should not be exceeded to keep Earth's systems stable. It assesses product impacts against these global thresholds, ensuring that they stay within a "safe operating space" for humanity. In PEF 3.1, it helps evaluate whether a product's environmental effects respect these boundaries.

Another way is to use the method of an aggregated weighting set (AWS), which aggregates the results based on a predefined set of weighting factors. It quantifies a product's environmental impact by assigning weights to various impact categories and combining them into a single score. This simplifies complex environmental data, making it easier to compare products and make informed decisions. In PEF 3.1, AWS provides a clear, aggregated assessment of a product's overall environmental performance. In this case a 25:25:50 of weighting approach is used. The results for both methods are shown in Table 11 and their differences highlighted in Figure 24 using PB and Figure 25 using AWS. The next two Figures, Figure 22 and Figure 23 show a more detailed results of the impacts broken down to every life cycle stage. For reasons of clarity, related Table containing all values per unit can be found in the Appendix, in Table 40 and Table 41.

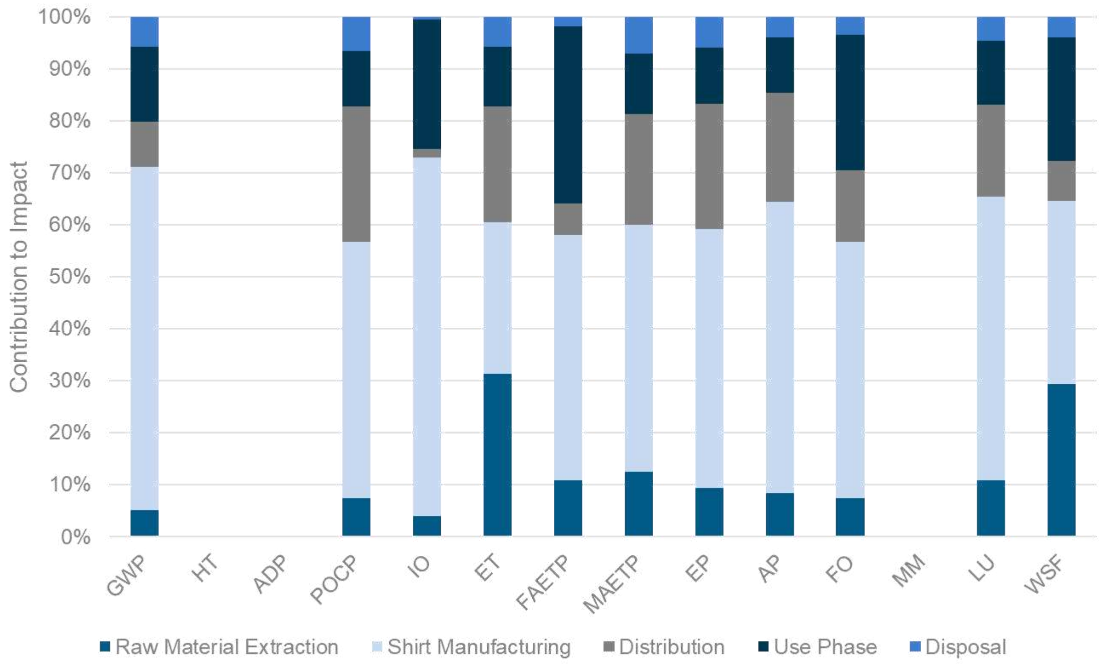

Figure 22: LCIA – Impact per Life Cycle Stages for Scenario A (PEF 3.1)

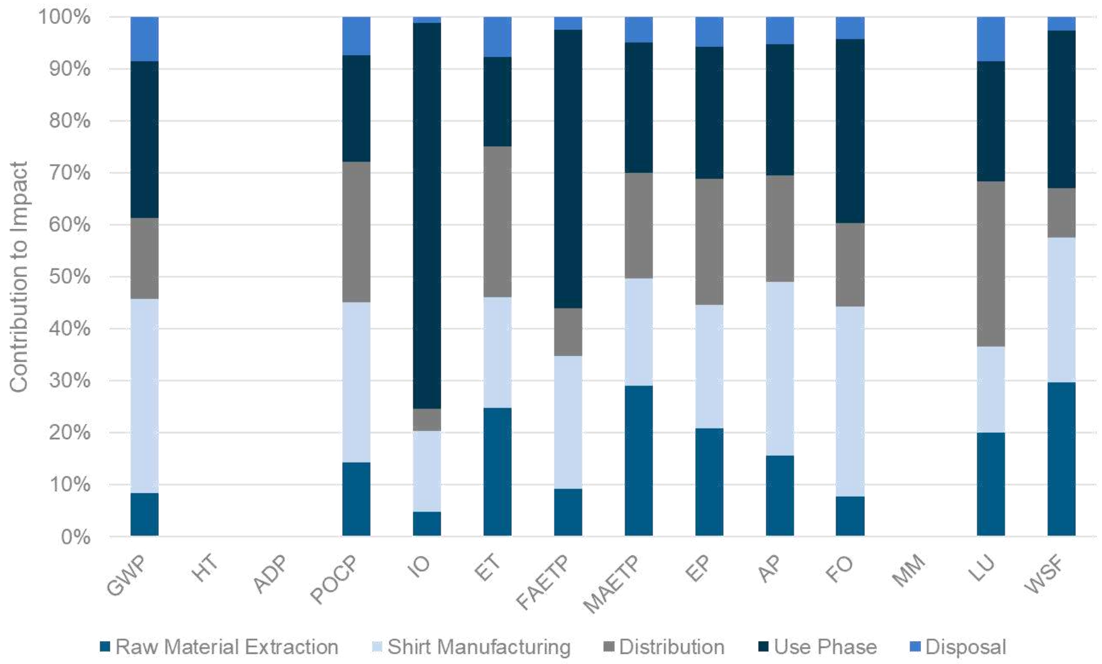

Figure 23: LCIA – Impact per Life Cycle Stages for Scenario B (PEF 3.1)

Table 11: Impact Assessment for scenarios A and B (EF 3.1 – AWS & PB)

	Impact Categories			Normalization [person*yr]		Results AWS* [points]		Results PB** [points]	
Impact Category	A	B	Unit	A	B	A	B	A	B
Climate change	5,487	2,604	kg CO2-Eq	0,001	0,000	0,008	0,004	0,006	0,003
Human health	0,000	0,000	CTUh	0,000	0,000	0,000	0,000	0,000	0,000
Freshwater ecotoxicity	16,938	11,389	CTUe	0,001	0,001	0,009	0,006	0,014	0,009
Freshwater eutrophication	0,001	0,001	kg P-Eq	0,000	0,001	0,004	0,002	0,004	0,003
Marine eutrophication	0,005	0,002	kg N-Eq	0,000	0,000	0,000	0,000	0,001	0,000
Terrestrial eutrophication	0,044	0,019	mol N-Eq	0,000	0,000	0,001	0,000	0,001	0,000
Freshwater and terrestrial acidification	0,018	0,007	mol H+ -Eq	0,000	0,000	0,002	0,001	0,001	0,000
Photochemical ozone creation	0,013	0,007	kg NMVOC-Eq	0,000	0,000	0,002	0,001	0,002	0,001
Ionizing radiation	0,600	0,202	kBq U235-Eq	0,000	0,000	0,000	0,000	0,001	0,000
Land use	12,298	6,512	points	0,000	0,000	0,000	0,000	0,014	0,000
Water scarcity	0,587	0,455	m³ world-Eq	0,000	0,000	0,000	0,000	0,000	0,000
Fossils	46,118	33,850	MJ	0,001	0,001	0,005	0,004	0,006	0,004
Minerals and metals	0,000	0,000	kg Sb-Eq	0,000	0,000	0,001	0,001	0,001	0,001
Sum of weighted impact categories						0,021	0,024	0,035	0,039

[27] *AWS – Aggregated weighting (25:25:50 approach), **PB – Planetary Boundaries

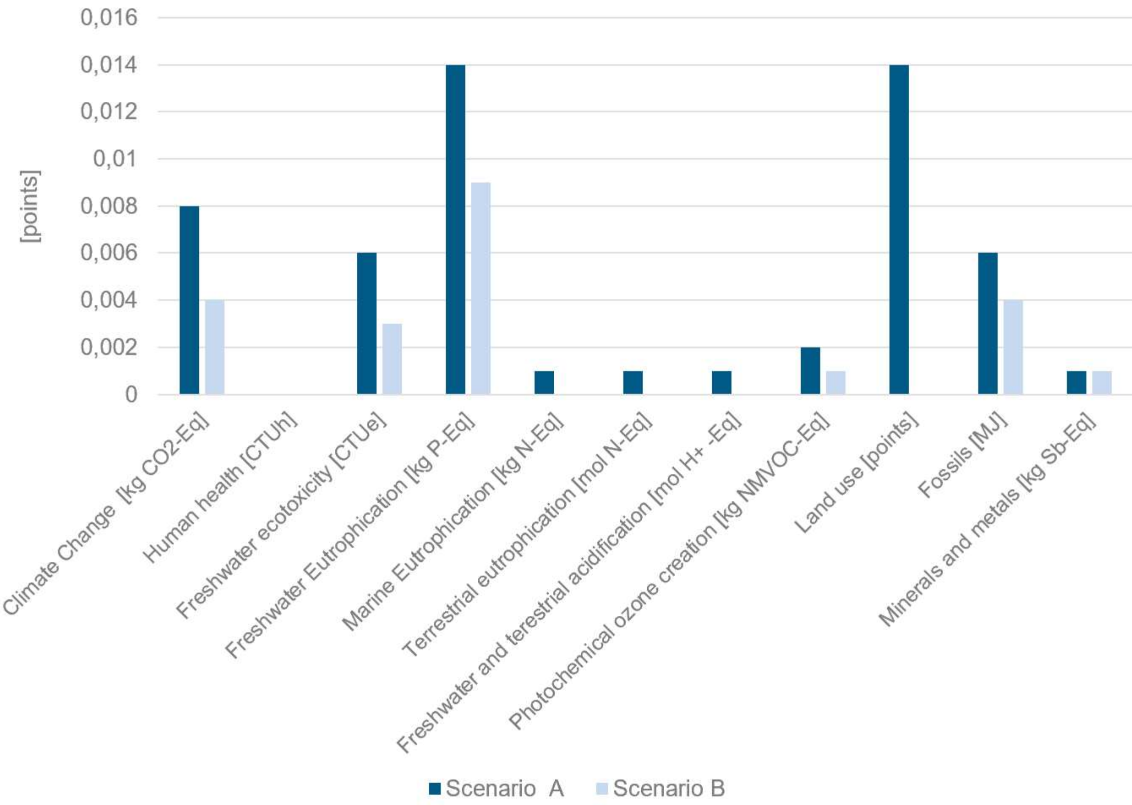

Figure 24: Planetary Boundaries Impact of Scenarios A and B (PEF 3.1)

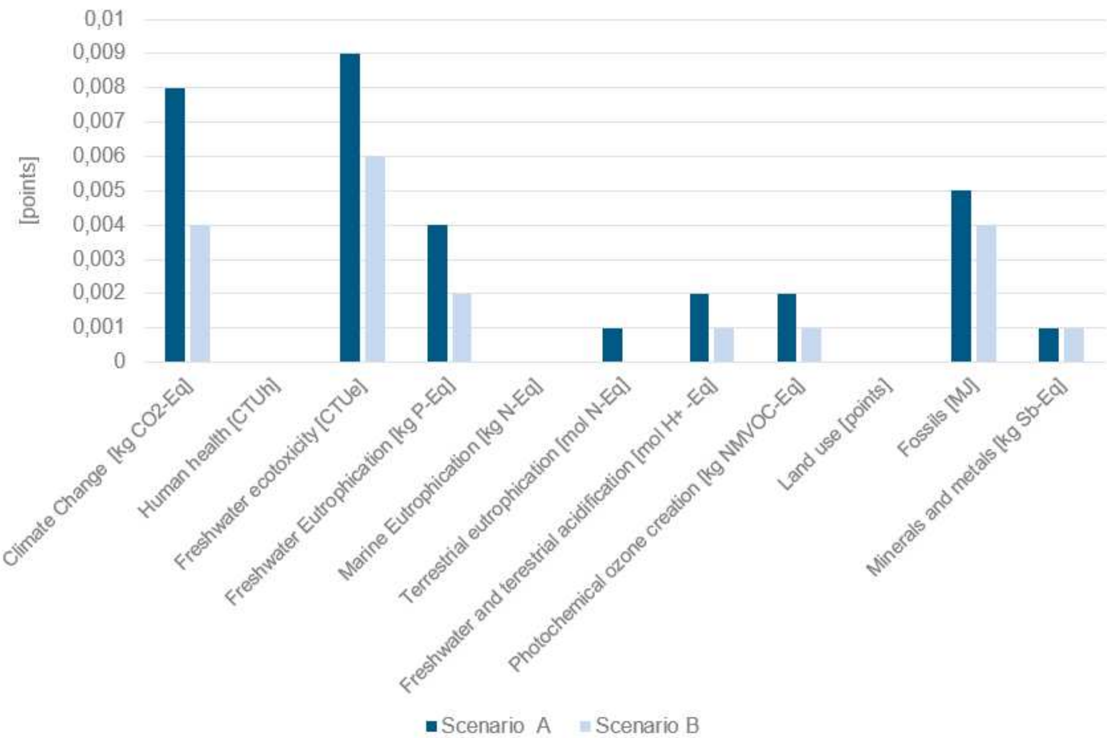

Figure 25: Aggregated Weighting Impact of Scenarios A and B (PEF 3.1)

4.6 Interpretation

As prescribed by the ISO 14040, the final step of a complete LCA is to analyze and interpret the findings from the Life Cycle Inventory Assessment. Thus, the results of the impact categories, conducted through EF3.1 and ICPP method are analyzed, while identifying relevant hotspots. The hotspot analysis aims to pinpoint the life cycle stages of the cotton T-shirt that are most significantly responsible for the overall environmental impact. Besides that, a comparison between both scenarios A and B, a Global and a European Production is made. By focusing on these key areas, improvements that have the greatest effect on reducing the product's environmental footprint can be targeted.

After that, a sensitivity analysis is carried out, to reflect on assumed parameters, to understand the robustness of the results from the LCIA and to discuss possible uncertainties. (see Chapter 4.6.4)

4.6.1 Hotspot Analysis for Scenario A

Scenario A represents the life cycle of a conventional global cotton T-Shirt, involving conventional cotton cultivation in the USA, standard partly automated textile manufacturing processes in Bangladesh, and typical consumer use and disposal practices in Germany.

Having a closer look on the global warming potential calculated with IPPC in Scenario A, the shirt manufacturing stage, specifically the cultivation of conventional cotton, emerges as a significant hotspot, contributing approximately 63% to the shirt manufacturing stage and 36% to the total global warming impact. Secondly, the mechanical drying is responsible for 28% of all CO_2 emissions, although it is assumed that only 10% of all washes are dried mechanically. Summing up all environmental impacts caused by producers, e.g. cradle-to-gate, 4,331 kg CO_2 is emitted, which corresponds to around 53% of all emissions. An overview of all CO_2 emissions by process step is shown below in Figure 26:

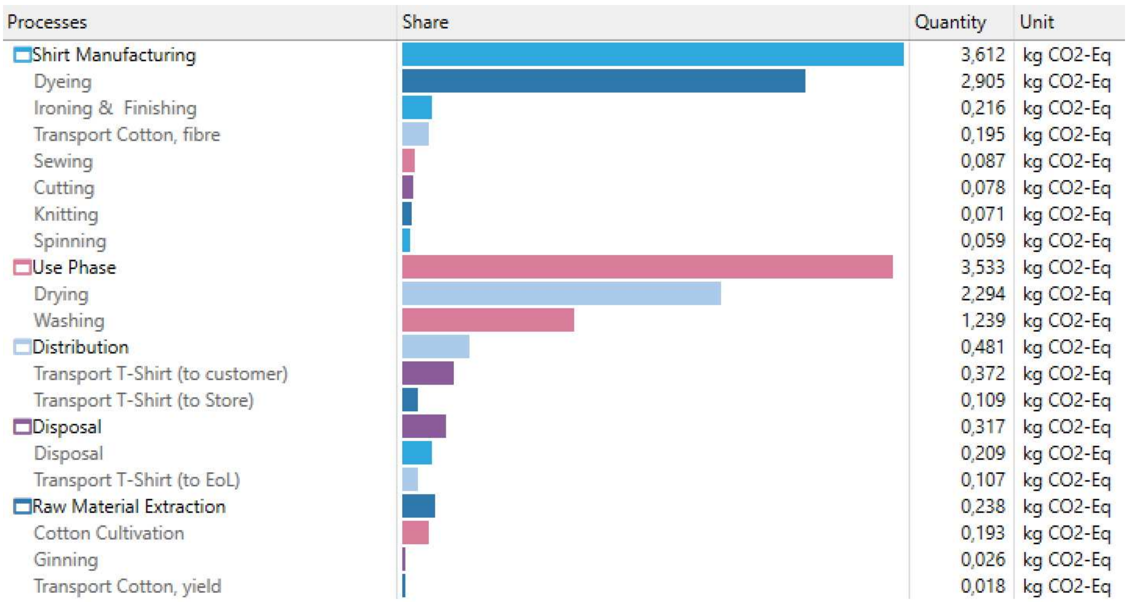

Figure 26: Hotspot Analysis – Scenario A (IPCC)

Analyzing the impact categories calculated with EF3.1 method while breaking them down into the different life cycle stages lead to the following results shown in Table 12:

Table 12: Hotspot Analysis – Scenario A (EF3.1)

	Raw Material Extraction	Shirt Manufacturing	Distribution	Use Phase	Disposal	Total	Unit
GWP	5,2%	65,9%	8,8%	14,3%	5,8%	5,478	CO2
HT	0,0%	0,0%	0,0%	0,0%	0,0%	0,000	CTUh
ADP	0,0%	0,000	0,000	0,000	0,000	0,000	CTUe
POCP	7,4%	49,3%	26,2%	10,6%	6,6%	0,013	kg NMVOC
IO	4,0%	69,0%	1,5%	25,1%	0,4%	0,600	kBq
ET	31,3%	29,1%	22,2%	11,5%	5,8%	16,938	CTUe
FAETP	0,0%	0,000	0,000	0,000	0,000	0,001	kg P
MAETP	12,5%	47,5%	21,3%	11,6%	7,1%	0,005	kg N
EP	9,4%	49,8%	24,0%	10,9%	5,9%	0,044	mol N
AP	8,4%	56,1%	20,9%	10,7%	3,9%	0,018	mol H+
FO	7,4%	49,3%	13,7%	26,1%	3,5%	46,118	MJ
MM	0,0%	0,000	0,000	0,000	0,000	0,000	kg Sb
LU	10,9%	54,6%	17,6%	12,3%	4,7%	12,298	points
WSF	29,3%	35,3%	7,7%	23,7%	3,9%	0,584	m³

As visible in Table 12, the hotspot analysis of the T-Shirt reveals that shirt manufacturing consistently emerges as the most significant contributor to environmental impacts across various categories. Specifically, it accounts for the highest percentage in global warming potential (65,9%), acidification potential (56,1%), photochemical ozone creation potential (49,3%), ionizing radiation (69,0%), and land use (54,6%), among others. This indicates that the manufacturing stage is the most carbon-intensive and resource-demanding phase of the T-shirt's life cycle. Raw material extraction also plays a crucial role, particularly in the water scarcity footprint (29,3%) and ecotoxicity (31,3%), underscoring the environmental burden of cotton cultivation, especially in water-stressed regions. The use phase and distribution stages are significant in categories such as fossil fuel depletion (26,1% and 13,7%, respectively), photochemical ozone creation potential (10,6% and 26,2%), and ecotoxicity (22,2% and 11,5%), highlighting the impact of consumer behavior and transportation logistics. Disposal generally has a lower impact but still contributes to the overall environmental footprint, particularly in categories like global warming potential (5.8%) and acidification potential (3,9%).

4.6.2 Hotspot Analysis for Scenario B

Scenario B illustrates the life cycle of an in solely Europe produced cotton T-Shirt, involving cotton cultivation in Türkiye, fully automated textile manufacturing processes in Türkiye and Austria, and typical consumer use and disposal practices in Germany.

The global warming potential calculated using IPCC method shows that the use phase is responsible for nearly 2/3 of all emissions, making it the biggest hotspot in this scenario. This is also the case, since shirt manufacturing emits 0,973 kg CO2, only 18% of GWP. The dyeing process is the most intense contributor to that stage with nearly 87% of all emissions in this stage. Summing up all environmental impacts caused by producers, e.g. cradle-to-gate, 1,597 kg CO_2 is emitted, which corresponds to around 30% of all emissions. An overview of all CO_2 emissions by process step is shown below in Figure 27:

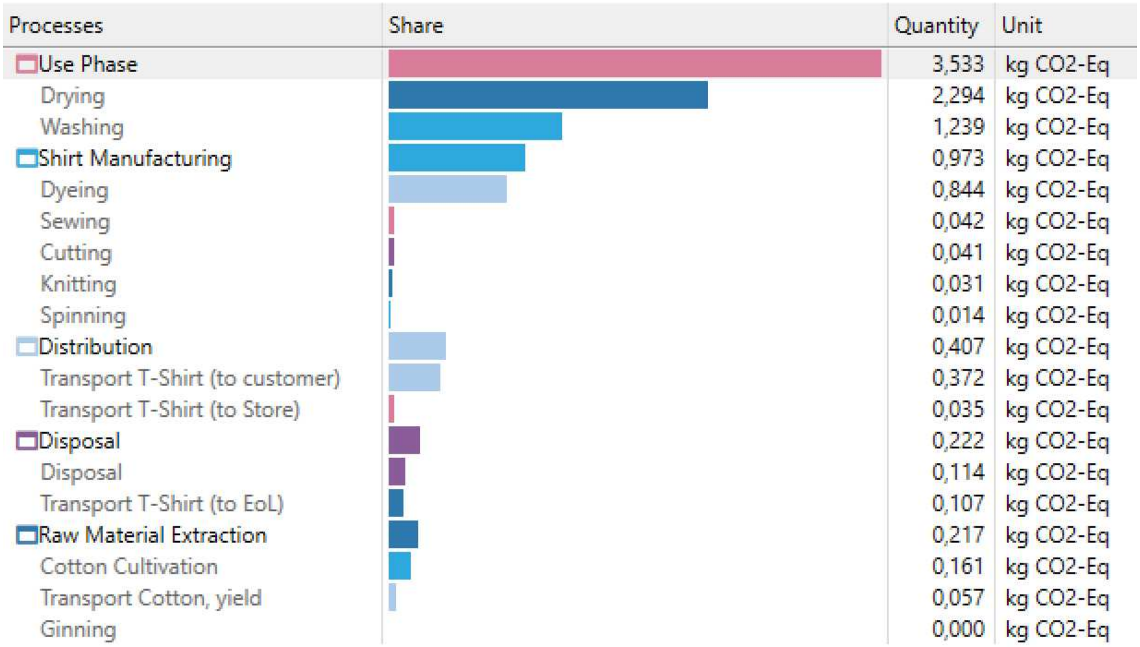

Figure 27: Hotspot Analysis – Scenario B (IPCC)

Analyzing the impact categories calculated with EF3.1 method while accounting them to the different life cycle stages lead to the following results shown in Table 13:

Table 13: Hotspot Analysis – Scenario B (EF3.1)

	Raw Material Extraction	Shirt Manufacturing	Distribution	Use Phase	Disposal	Total	Unit
GWP	8,3%	37,4%	15,6%	30,2%	8,5%	2,604	CO2
HT	0,000	0,000	0,000	0,000	0,000	0,000	CTUh
ADP	14,3%	30,7%	27,1%	20,5%	7,4%	0,007	CTUe
POCP	4,7%	15,7%	4,2%	74,3%	1,1%	0,202	kg NMVOC
IO	24,8%	21,3%	29,1%	17,1%	7,8%	11,389	kBq
ET	0%	0%	0%	0%	0%	0,001	CTUe
FAETP	29,1%	20,7%	20,3%	25,1%	4,9%	0,002	kg P
MAETP	20,9%	23,7%	24,2%	25,5%	5,8%	0,019	kg N
EP	15,6%	33,5%	20,4%	25,4%	5,2%	0,007	mol N
AP	7,8%	36,5%	16,0%	35,5%	4,2%	33,850	mol H+
FO	0,000	0,000	0,000	0,000	0,000	0,000	MJ
MM	20,0%	16,7%	31,8%	23,2%	8,4%	6,512	kg Sb
LU	29,7%	27,9%	9,4%	30,4%	2,6%	0,455	points
WSF	8,3%	37,4%	15,6%	30,2%	8,5%	2,604	m³

Taking the numbers shown in Table 13 into account, shirt manufacturing is a significant hotspot, particularly in categories such as global warming potential, where it contributes 37.4%, and water scarcity footprint, also at 37.4%. The manufacturing stage is a critical phase, particularly for energy-intensive processes, leading to substantial contributions to GWP and water use. Raw material extraction plays a notable role in several impact categories, particularly in ionizing radiation with 24.8%, freshwater eutrophication with 29.1%, and land use with 29.7%. These figures indicate the environmental burden associated with the sourcing of raw materials, particularly in terms of radiation and land occupation impacts. Distribution also emerges as a key contributor, particularly in ionizing radiation (29.1%), mineral resource depletion (31.8%), and marine aquatic ecotoxicity potential (24.2%). This stage involves the transportation and logistics aspects of the T-shirt's life cycle, which are highly energy-intensive and resource-demanding.

The use phase is particularly dominant in the photochemical ozone creation potential (POCP) with 74.3% and acidification potential with 35.5%. This suggests that consumer behavior, such as washing and drying practices, has a significant impact on these categories, contributing to the formation of ground-level ozone and acidifying emissions.

Disposal generally has a lower impact compared to other stages but still contributes to categories like global warming potential (8,5%), acidification potential (4.2%), and mineral resource depletion (8,4%). Although smaller in magnitude, the disposal stage's impact should not be overlooked.

4.6.3 Comparative Hotspot Analysis

Comparing the two scenarios A and B with each other, as visible in Figure 21, a relative decrease of 34,6% of CO_2 emissions is notable. Moreover, it becomes clear that the biggest difference lies in the Shirt Manufacturing stage. Whereas in scenario A, the impact is 3,612 kg, scenario B only shows an impact of 0,973 kg, which is a reduction of about 27%. The below Table 14 shows a breakdown of all process steps, including a further calculated discrepancy to showcase the differences between scenario A and B in more detail:

Table 14: Hotspot Analysis – Comparative CO_2 Impact

Life Cycle stage	Process step	Scenario A	Scenario B	Discrepancy
Raw Material Extraction	Cotton Cultivation	0,193	0,161	**-3%**
	Transport Cotton, yield	0,018	0,057	**+4%**
	Ginning	0,026	Almost 0	**0%**
Shirt Manufacturing	Transport Cotton, fiber	0,195	Almost 0 Almost 0	**-20%**
	Spinning	0,059	0,014	**-5%**
	Knitting	0,071	0,031	**-4%**
	Dyeing	2,905	0,844	**-206%**
	Cutting	0,078	0,041	**-4%**
	Sewing	0,087	0,042	**-5%**
	Ironing & Finishing	0,216	-	**0%**
Distribution	Transport T-Shirt (to Store)	0,109	0,035	**-7%**
	Transport T-Shirt (to Customer)	0,372	0,372	**0%**
Use Phase	Washing	1,239	1,239	**0%**
	Drying	2,294	2,294	**0%**
Disposal	Transport T-Shirt (to EoL)	0,107	0,107	**0%**
	Disposal, T-Shirt	0,209	0,114	**-10%**
Total impact		**8,178 kg CO2-Eq/Shirt**	**5,351 kg CO2-Eq/Shirt**	**-35%**

As visible in Table 14, nearly every stage shows a decreased CO_2 impact in scenario B, except the transport of cotton yield to the gin. This is due to the bigger distance assumed between the cotton field and the ginning facility, which might be different in practice. One main process step stands out, the dyeing process, with a decrease of 206%. Although the use of dying auxiliaries can make a tremendous impact, this would need further inspection, especially about the mappings used. (See Another notable difference is visible in the cotton fiber transport (20%), which can be traced back to the big impact created by container ship transport in scenario A. The decrease of 10% for the disposal of the T-Shirt is a result of the assumed reduced overproduction from 30% (scenario A) to 15% (scenario B), which ice possible to shorter lead times and thus a more precise calculation of demand.

Raw Material Extraction

In the raw material extraction stage, cotton cultivation under Scenario B shows a slight reduction of 3% in CO_2-Eq emissions compared to Scenario A (0,161 kg CO_2-Eq vs. 0,193 kg CO_2-Eq). This could indicate that Scenario B incorporates more sustainable agricultural practices or more efficient resource use. However, transport of cotton yield presents a 4% increase in emissions in Scenario B (0,057 kg CO_2-Eq vs. 0,018 kg CO_2-

Eq), which can be traced back to longer transport distances assumed. The ginning process is only present in Scenario A, contributing 0,026 kg CO_2-Eq, but is absent in Scenario B, indicating a difference in the supply chain configuration or possibly an integrated ginning process within another stage.

Shirt Manufacturing

Processes such as spinning, knitting, cutting, and sewing also show reductions in Scenario B, with decreases ranging from 4% to 5%. However, the most significant reduction is observed in the dyeing process, with Scenario B showing a 206% decrease in emissions (0,844 kg CO_2-Eq in Scenario B vs. 2,905 kg CO_2-Eq in Scenario A). Although a substantial adoption of less energy-intensive dyeing techniques or the use of environmentally friendly dyes in Scenario B.

Additionally, the ironing and finishing process, which contributes 0,216 kg CO_2-Eq in Scenario A, is completely neglected in Scenario B, since it is not necessary when using the automated way of production, implementing a sewing robot, which is able to carry the material without any wrinkles.

Distribution

In the distribution stage, Scenario B shows a notable decrease in emissions related to the transport of T-shirts to stores, with a 7% reduction compared to Scenario A (0,035 kg CO_2-Eq vs. 0,109 kg CO_2-Eq). This suggests more efficient logistics or potentially shorter distances involved in transporting the final product to retail locations. However, the transport of T-shirts to customers remains unchanged across both scenarios, maintaining a constant contribution of 0,372 kg CO_2-Eq**.** This indicates that the direct-to-consumer logistics are likely standardized across both scenarios, possibly due to similar delivery methods or geographic distributions.

Use Phase

The use phase, which includes washing and drying of the T-shirts, remains identical in both scenarios, contributing 1,239 kg CO_2-Eq and 2,294 kg CO_2-Eq, respectively. This phase represents a significant portion of the overall life cycle emissions and highlights the importance of consumer behavior and the energy efficiency of household appliances in determining the environmental impact of textile products. Despite the overall improvements in manufacturing and distribution, the use phase remains a major contributor to the total CO_2-Eq emissions.

Disposal

Finally, the disposal stage also shows differences between the two scenarios. Transport to end-of-life sites remains constant at 0,107 kg CO_2-Eq across both scenarios. However, the disposal process itself sees a 10% reduction in Scenario B (0,114 kg CO_2-Eq vs**.** 0,209 kg CO_2-Eq)**,** which can be traced back to the reduced level of overproduction.

Overall Impact

The cumulative impact of these changes results in a total CO_2-Eq emission of 5,351 kg per shirt in Scenario B, representing a 35% reduction from the 8,178 kg CO_2-Eq observed in Scenario A. This substantial decrease highlights the effectiveness of the improvements implemented in Scenario B, particularly in the manufacturing and disposal stages, where the most significant reductions are achieved.

In summary, the hotspot analysis revealed that cotton cultivation and manufacturing are the two most critical stages in terms of environmental impact. Addressing these hotspots will be essential for improving the overall sustainability of the cotton T-shirt. However, there are still some uncertain values that need more attention, and will therefore be further separately analyzed in Chapter 4.4.4.

4.6.4 Sensitivity Analysis

As already mentioned in Chapter 4.3.2, in both product systems/scenarios, the LCA of producing, using, and disposing of a 100% Cotton T-shirt is conducted. Although the process steps are similar, they differ because of the omitted “ironing” step and the additional Transport of Cotton Fiber between “Wet Processing” and “Making-Up” in the fully automated process (see Appendix). Due to different figures available in the literature and ways to produce as a manufacturer and act as a consumer respectively, a sensitivity analysis is conducted. This analysis will focus on three critical variables:

- **Material losses** during Shirt Manufacturing Stages (Spinning, Knitting, Dyeing, Cutting, Sewing)
- **Overproduction** factor
- **Lifespan** of a T-Shirt (= Amounts of Washes done by the consumer before Disposal)

The overproduction factor accounts for the discrepancy between the number of T-shirts produced and those actually sold, reflecting potential wastage due to unsold inventory. Material losses during shirt manufacturing consider inefficiencies in the production process, such as fabric waste during cutting or defects leading to discarded garments, an essential indicator for the fashion industry (as described in more detail in chapter 2.3.3). The lifespan of a T-shirt is another crucial parameter, as it directly affects the use phase, which has a significant impact on the product’s overall environmental footprint, as seen in Table 9)

To measure these effects, the analyzed parameters are slightly changed, in increments of 5% (for overproduction), and assumptions for the best- and worst-case regarding the material losses. Each parameter is changed independently from all others so that the magnitude of its effect on the base case can be assessed. The ultimate figures chosen can be seen in the tables below and its results are subsequently discussed.

Material Losses

As already described above, throughout the shirt manufacturing stage, several losses of materials occur. This can mostly either be traced back to the human mistakes or machine defects. The numbers chosen for the base line scenario was 30%. Since overproduction is a parameter, that fashion retailer are trying to decrease, only lower percentages are used for the other scenarios – seen in Table 15 (Scenario A) and Table 16 (Scenario B).

Overproduction factor

The first parameter analyzed is the overproduction factor, as shown for both scenarios respectively in Table 15 and Table 16:

Table 15: Sensitivity analysis – Overproduction (Scenario A)

Overproduction factor	Base Case 30%	25%	20%	15%
Raw Material Extraction	0,238	0,228	0,219	0,21
Shirt Manufacturing	3,612	3,481	3,351	3,22
Distribution	0,481	0,477	0,473	0,468
Use Phase	3,533	3,533	3,533	3,533
Disposal	0,317	0,308	0,3	0,291
Total CO_2 Impact	**8,181**	**8,027**	**7,876**	**7,722**
Relative Difference		**-1,9%**	**-3,7%**	**-5,6%**

As notable in Table 15, the sensitivity analysis reveals that reducing the overproduction factor leads to a noticeable decrease in the total CO_2 impact of T-shirt production. Starting with a 30% overproduction factor, the total CO_2 impact is 8,181 kg CO_2-Eq. When the overproduction is reduced to 25%, 20%, and 15%, the CO_2 impact decreases, while the most significant reduction in emissions occurs in the shirt manufacturing stage, where the CO_2 impact drops from 3,612 kg CO_2-Eq at 30% overproduction to 3,22 kg CO_2-Eq at 15%. This indicates that manufacturing processes are highly sensitive to overproduction, likely due to energy-intensive operations and material usage. The raw material extraction and disposal stages also experience reductions, though to a lesser extent. The use phase remains constant across all scenarios, reflecting that consumer usage is unaffected by production volume.

Table 16: Sensitivity analysis – Overproduction (Scenario B)

Overproduction factor	20%	Base Case 15%	10%	5%
Raw Material Extraction	0,227	0,217	0,208	0,199
Shirt Manufacturing	1,015	0,973	0,93	0,888
Distribution	0,408	0,407	0,405	0,404
Use Phase	3,533	3,533	3,533	3,533
Disposal	0,226	0,222	0,218	0,214
Total CO_2 Impact	**5,409**	**5,352**	**5,294**	**5,238**
Relative Difference	**+1,1%**		**-1,1%**	**-2,1%**

The total CO_2 impact decreases gradually from 5,352 kg CO_2-Eq at a 215% overproduction factor to 5,238 kg CO_2-Eq at a 5% factor, with a relative difference ranging from +1,1% to -2,1% compared to the base case. The most significant reductions occur in the Shirt Manufacturing and Raw Material Extraction stages, while the Use Phase remains constant, highlighting its independence from production levels. The Disposal and Distribution stages show modest decreases, with the latter being the least responsive to changes in overproduction. This analysis underscores the importance of optimizing production processes to achieve environmental benefits, particularly in the energy-intensive manufacturing stage, while also acknowledging the relatively stable impact of the use and distribution phases.

Life Span

Conducting a LCA with the assumption of 44 times use before disposal, the total impact is 5,442 kg CO_2. When carrying out a sensitivity analysis for that parameter, only the use phase is affected, since it has no directly visible impact, whether on upstream nor downstream process steps. Reducing the number of washes by half results in a 34,1% decrease in total CO_2 impact, bringing it down to 3,585 kg CO_2-Eq. The use phase impact is halved, reflecting the direcst correlation between the number of washes and the environmental burden of the use phase. Further reduction to 11 washes leads to a 50,3% reduction in total impact, with the CO_2 emissions dropping to 2,702 kg CO_2. The use phase now represents a smaller portion of the overall emissions, though it still remains the dominant factor. In the extreme case of just one wash, the total CO_2 impact decreases by 65.1%, down to 1,899 kg CO_2. Here, the use phase's contribution is minimal (0,08 kg CO_2) and the impacts from other stages like raw material extraction and shirt manufacturing become relatively more significant.

Table 17: Sensitivity analysis – Life span (Scenario A & B)

Number of Washes	Base Case 44	22	11	1
Raw Material Extraction	0,217	0,217	0,217	0,217
Shirt Manufacturing	0,973	0,973	0,973	0,973
Distribution	0,497	0,407	0,407	0,407
Use Phase	3,533	1,766	0,883	0,08
Disposal	0,222	0,222	0,222	0,222
Total CO_2 Impact	**5,442**	**3,585**	**2,702**	**1,899**
Relative Difference		**-34,1%**	**-50,3%**	**-65,1%**

4.6.5 Uncertainties

Although reasonable assumptions to acquire the distance data of cotton transportation and T-shirt distribution, as well as use-phase data, have been made, there exist several uncertainties related to distance calculations and consumer behavior. However, a sensitivity analysis is to examine the effects of varying the base case for those parameters is neglected, since the data availability of other data is quite limited and would therefore lead to no further solution.

4.7 Economical Perspective of Shirt Manufacturing

In addition to the ecological perspective, it's essential to consider the economic factors to gain a comprehensive understanding of the scenarios and their practical implementation. This chapter presents a comparative investment analysis focused on the shirt manufacturing stage, examining different production locations. The analysis compares conventional production methods with automated production using sewing robots. The data used is a combination of secondary sources and confidential internal information, and the evaluation is conducted using static investment methods outlined in Chapter 3.2.2.

Disclaimer: Machinery costs and production time are both assumed for the purpose of showing potential economic effects. In practice, according to silana the machinery costs will lay between 200.000 € and 1.000.000 €.

4.7.1 Background calculations and assumptions

In order to conduct a cost comparison, several background calculations or assumptions regarding the production itself must be done:

- Number of produced T-Shirts/year
- Depreciation costs of the machine
- Wages per year
- Custom fees
- Electricity

Number of produced T-Shirts

The number of produced T-Shirts depends on the load factor and the duration for producing one T-Shirt. Assuming that it takes 3 minutes in total to sew one T-Shirt, and the production is done 24 hours per day, the following amount of T-Shirts can be produced per year, shown in Table 18:

Table 18: Number of produced T-Shirts per year

	Scenario B	Scenario A
T-Shirt / minute / machine	0,3333333	0,3333333
T-Shirts / days	480	480
Production days	365	365
# Machines	10	10
Success rate	96 %	92 %
Capacity rate	95 %	95 %
T-Shirts / year	**1597824**	**1531248**

As visible in Table 19, the success rate of the sewing robot is 4% higher. This is because of more accurate work, which can be achieved by eliminating human error. For the purpose of simplification all following calculations are done assuming that 1 600 000 T-Shirts are produced for both scenarios.

Depreciation costs of the machine

In general, the calculation depreciation costs are calculated using the following formula:

Equation 4: Depreciation costs

$$Depreciation\ value = \frac{Acquisition\ costs}{Expected\ useful\ life}$$

In the case of the sewing robot used in Scenario B or rather the sewing machine, used in Scenario A, the results are as follows in Table 19:

Table 19: Depreciation costs of sewing machines and sewing robot

	Costs	Number	Depreciation in years	AfA
Scenario B	€ 350 000,00	10	8	**€ 437 500,00**
Scenario A	€ 3 000,00	9	6	**€ 4 500,00**

Wages per year

Another component of the cost analysis is the wage of garment workers, which can be significantly shortened for a fully automated production line, where less than 5% of garment workers' staff is needed due to automation. The actual cost for wages per year needs to be calculated for every case respectively, since this number varies from country to country. An overview of the wages of garment workers for relevant countries used in the following scenarios can be found in Table 20:

Table 20: Wages per year and producing country

Country	Average wage per year	Minimum wage per year	Source
China	**€ 10 670,40**	€ 6 983,32	(China Briefing News, 2024)
USA	**€ 37 000,00**	€ 15 734,12	(Velocity Global, 2024)
Turkey	**€ 9 703,45**	€ 8 821,32	(WageIndicator Foundation, 2024)
Austria	**€ 36 507,00**	€ 23 248,00	(Finanzrechner.at, 2022)
Bangladesh	**€ 1 500,00**	€ 1 200,00	(Fair Labor Association, 2024)

Custom fees

The custom fees play a critical role in terms of the overall costs, since e.g. the tariff to the EU from China makes up 12%, whereas Bangladesh is excepted from paying customs, as shown in Table 21:

Table 21: Custom fees to EU

Country	Tariff to EU
China	12 %
USA	0 %
Turkey	0 %
Bangladesh	0 %

Electricity use

When it comes to electricity use, there are also significant differences between both scenarios, either semi-automated using sewing machines or fully-automated using a sewing robot from silana. On the one hand, using conventional sewing machines, a step of ironing is needed, which intensifies the needed amount of electricity. It is assumed that 90% of workers use a sewing machine, while 10% are occupied with ironing. On the other hand, the new sewing machines including the robot components lead to an even higher amount of electricity need, as seen in Table 22:

Table 22: Electricity use – Scenario A vs. Scenario B

	Scenario A – conventional		**Scenario B – fully automated**		
	Sewing machines	Ironing	Sewing machines	Artificial Arm	Negative Pressure
Power in watts	200	2500	180	2400	4000
Number	19	1,9	20	10	10
Hours per day	24	24	24	24	24
Days per year	365	365	365	365	365
Watt hours per year	33288000	416100000	31536000	210240000	350400000
kWh per year	33288	41610	31563	210240	350400
Overall electricity use	**74898 kWh**		**592176 kWh**		

4.7.2 Bangladesh vs. Türkiye

The first comparison is done between the two countries already compared in the LCA – Bangladesh and Türkiye. It is assumed that the production in Bangladesh is done semi-automated, whereas the production in Türkiye is carried out fully automated:

Table 23: Cost comparison – Bangladesh vs. Türkiye

	Bangladesh (semi-automated)	Türkiye (fully automated)
Material (including trims)	€ 1,02	€ 0,98
Processing and Overhead (handling, cutting, …)	€ 0,25	€ 0,25
Wage costs / T-Shirt	€ 0,07	€ 0,11
Machinery cost / T-Shirt (rent/depreciation)	€ 0,003	€ 0,27
Electricity costs	€ 0,01	€ 0,05
Margin producer	**€ 0,64**	**€ 0,44**
FOB Price	€ 2,00	€ 3,00
Logistics	€ 0,04	€ 0,06
Customs	€ -	€ -
Intermediary	€ 0,50	€ -
Landed Cost	€ 2,54	€ 3,06

As visible in Table 27, the comparison between semi-automated production in Bangladesh and fully automated production in Türkiye highlights key differences in costs. Material and processing costs are similar between the two countries, but wage costs are slightly lower in Bangladesh (€0,07) compared to Türkiye (€0,11). Machinery costs are minimal in Bangladesh (€0,003) but significantly higher in Türkiye (€0,27), reflecting the investment in full automation.

Despite the higher machinery and electricity costs, Türkiye is assumed to have a higher FOB price (€3,00) and thus higher landed cost (€3,06) than Bangladesh. However, Türkiye's fully automated process results in additional profit per T-shirt (€0,76) and total additional profit (€1.223.364,77), although with a longer payback time of 2,11 years compared to the other examples. The -352% cost reduction, depicted in Table 28, indicates an increase in costs due to automation. However, in the end this is offset by the higher profit margins, as seen in Table 24:

Table 24: Results of cost comparison – Bangladesh vs. Türkiye

Cost reduction in the sewing process	**-352%**
Additional Profit in total	€ 1 223 364,77
Additional Profit per machine	€ 122 336,48
Additional Profit per T-Shirt	**€ 0,76**
Packback-Time in years	**2,11**

4.7.3 Bangladesh vs. Austria

The next case analyzed in terms of its costs is a comparison between a semi-automated production line in Bangladesh and a fully automated production in Austria, as showcased in the following Table 25:

Table 25: Cost comparison – Bangladesh vs. Austria

	Bangladesh (semi-automated)	Austria (fully automated)
Material (including trims)	€ 1,02	€ 0,98
Processing and Overhead (handling, cutting, …)	€ 0,25	€ 0,25
Wage costs / T-Shirt	€ 0,09	€ 0,11
Machinery cost / T-Shirt (rent/depreciation)	€ 0,003	€ 0,27
Electricity costs	€ 0,01	€ 0,05
Margin producer	**€ 0,64**	**€ 2,34**
FOB Price	€ 1,5	€ 4,00
Logistics	€ 0,10	€ 0,04
Customs	€ -	€ -
Intermediary	€ 0,50	€ -
Landed Cost	€ 2,60	€ 4,04

As visible in Table 25, a comparison of the costs associated with producing a T-shirt in Bangladesh (semi-automated) versus Austria (fully automated) is done. In Bangladesh, the material costs are slightly higher (€1,02) compared to Austria (€0,98), while wage costs per T-shirt are lower (€0,09 vs. €0,11). The small gap between the wages lays in the significantly reduced amount of employees needed for an automated production. However, due to automation, the fully automated process results in significantly higher machinery costs (€0,27 vs. €0,003) and electricity costs (€0,05 vs. €0,01). But since the FOB price in Austria is much higher, because “Made in Austria” can be sold for a higher price, the margin for the producer in Austria is also much higher (€2,34) compared to Bangladesh (€0,64).

Overall, the landed cost of a T-shirt is higher in Austria (€4,04) compared to Bangladesh (€2,60). However, Austria shows a notable cost reduction in the sewing process (-458%) due to automation. Additionally, automation in Austria results in a significant increase in profit: €2.691.575,60 in total, €269.157,56 per machine, and €1,71 per T-shirt, with a payback time of 1,10 years, as seen in

Table 26: Results of cost comparison – Bangladesh vs. Austria

Cost reduction in the sewing process	**-458%**
Additional Profit in total	€ 2 691 575,60
Additional Profit per machine	€ 269 157,56
Additional Profit per T-Shirt	**€ 1,71**
Packback-Time in years	**1,10**

4.7.4 China vs. Austria

The next differentiation is done between semi-automated production in China and fully automated production in Austria, depicted in Table 27:

Table 27: Cost comparison – China vs. Austria

	China (semi-automated)		Austria (fully automated)	
Material (including trims)	€	1,02	€	0,98
Processing and Overhead (handling, cutting, …)	€	0,25	€	0,25
Wage costs / T-Shirt	€	0,63	€	0,11
Machinery cost / T-Shirt (rent/depreciation)	€	0,00	€	0,27
Electricity costs	€	0,01	€	0,05
Margin producer	**€**	**0,09**	**€**	**2,34**
FOB Price	€	2,00	€	4,00
Logistics	€	0,10	€	0,04
Customs	€	0,33	€	-
Intermediary	€	-	€	-
Landed Cost	€	2,43	€	4,04

Table 27 reveals significant differences in cost structures between shirt manufacturing in China and Austria. Material costs are slightly lower in Austria (€ 0,98) compared to China (€ 1,02). However, wage costs are significantly lower in Austria (€ 0,08) than in China (€ 0,63), likely due to automation, which is further reflected in Austria's machinery cost per T-shirt (€ 0,27) compared to none in China (€ 0,00). Electricity costs are higher in Austria (€ 0,05) than in China (€ 0,01), possibly due to variations in energy pricing or usage. When looking at the overall pricing, Austria's FOB price (€ 4,00) and landed cost (€ 4,04) are significantly higher than China's (€ 2,00 and € 2,43, respectively), largely due to higher margin producer costs in Austria (€ 2,34) versus China (€ 0,09). Logistics and customs costs are higher in China (€ 0,10 and € 0,33) compared to Austria (€ 0,04 and € 0,00).

Table 28: Results of cost comparison – China vs. Austria

Cost reduction in the sewing process	**37%**
Additional Profit in total	€ 3 640 503,03
Additional Profit per machine	€ 364 050,30
Additional Profit per T-Shirt	**€ 2,28**
Packback-Time in years	**0,86**

Table 28 provides insights into the financial impact of automating the originally Chinese sewing process in Austria. It shows a 37% cost reduction, which significantly enhances profitability. The additional profit generated totals €3.640.503,03, with € 364.050,30 in profit per machine and € 2,28 per T-Shirt. Moreover, the payback time for the investment in automation is relatively short, at just 0,86 years. This indicates that automation could be a highly profitable investment, quickly covering its initial costs and providing substantial financial returns.

4.7.5 USA vs. USA

As a last case, the sole difference between producing semi-automated in comparison to fully automated in the USA is shown, to showcase the impact nearshoring through automation could have in America:

Table 29: Cost components – USA vs. USA

	USA (semi-automated)	USA (fully automated)
Material (including trims)	€ 1,02	€ 0,98
Processing and Overhead (handling, cutting, …)	€ 0,25	€ 0,25
Wage costs / T-Shirt	€ 2,20	€ 0,11
Machinery cost / T-Shirt (rent/depreciation)	€ 0,003	€ 0,27
Electricity costs	€ 0,01	€ 0,05
Margin producer	**€ 0,53**	**€ 2,34**
FOB Price	€ 4,00	€ 4,00
Logistics	€ 0,04	€ 0,04
Customs	€ -	€ -
Intermediary	€ -	€ -
Landed Cost	€ 2,43	€ 4,04

Table 29 compares the costs of producing a T-shirt in the USA using semi-automated versus fully automated processes. Material costs are slightly lower in the fully automated process (€0,98) compared to the semi-automated one (€1,02), with processing and overhead costs remaining the same (€0,25). However, the wage costs show a dramatic difference, dropping from €2,20 in the semi-automated process to just €0,11 in the fully automated one.

Despite the significant reduction in labor costs, the machinery and electricity costs in the fully automated process are much higher (€0,27 and €0,05, respectively) than in the semi-automated process (€0,003 and €0,01). The margin for the producer is also significantly higher in the fully automated process (€2,34) compared to the semi-automated one (€0,53). Despite these cost differences, the FOB price remains the same for both processes (€4,00).

Table 30: Results of cost comparison – China vs. Austria

Cost reduction in the sewing process	**81%**
Additional Profit in total	€ 2 903 979,88
Additional Profit per machine	€ 290 397,98
Additional Profit per T-Shirt	**€ 0,18**
Packback-Time in years	**1,05**

Critically, while the automation drastically cuts wage costs and increases the margin for producers, this comes with a substantial increase in machinery and electricity costs, raising questions about the sustainability of such automation. The landed cost is notably higher for the fully automated process (€4,04) compared to the semi-automated one (€2,43). Although, as seen in Table 30, automation offers an 81% reduction in sewing costs and promises significant additional profits (€2 903 979,88 in total, €290.397,98 per machine, and €0,18 per T-shirt) with a payback time of 1,05 years, the initial high costs and potential dependency on high-margin products may not be justifiable in all contexts.

4.7.6 Main findings

The comparison between semi-automated production in Bangladesh and the USA with fully automated production in Austria and the USA highlights both the significant advantages and the important considerations associated with automation. On the one hand, automation offers dramatic reductions in labor costs, particularly in high-wage countries like the USA, where wage savings are substantial. This reduction in labor expenses, coupled with increased efficiency and the ability to scale production, positions fully automated facilities as a strategic asset in competitive markets.

As seen in the comparison, automation also leads to significantly higher producer margins, enabling companies to achieve greater profitability – except differentiating between semi-automated production in Bangladesh and fully automated production in Türkiye. The consistent quality and faster production times associated with automated processes further enhance their appeal, especially in markets where speed and precision are crucial. The relatively short payback period for the investment in automation, alongside the potential for substantial additional profits, makes the case for automation strong.

However, it is important to consider also possible trade-offs. The higher machinery and electricity costs in fully automated setups, particularly in regions like Austria and the USA, can offset some of the savings from reduced wages. These increased operational costs could impact overall profitability if not carefully managed. Additionally, the higher FOB prices and landed costs associated with automation may challenge the market competitiveness of these products, especially in price-sensitive markets.

In conclusion, while automation offers significant benefits in terms of cost reduction, efficiency, and profitability, it also requires careful consideration of the associated costs and market dynamics. Moreover, a more precise and especially dynamic investment appraisal would be needed to clearly estimate the potential of automating the production process.

5 Summary and Outlook

This work provides a comprehensive analysis of the fashion industry's current production processes, focusing on the ecological and economic implications of transitioning from a semi-automated to a fully automated production model. The study begins by highlighting the initial problem: the fashion industry’s reliance on outdated production methods and its heavy impact on the environment due to extensive CO2 emissions, long supply chains, and poor labor conditions in low wage countries. To address these challenges, this research explores the potential of full automation in garment manufacturing, particularly using robotics in the sewing process.

The analysis employs a Life Cycle Assessment methodology, supported by the UMBERTO software and ecoinvent database, to compare the environmental impacts of a conventional global semi-automated production process with a European fully automated one. The findings show that full automation and reshoring production closer to the point of sale can significantly reduce the environmental impact of a cotton T-Shirt's life cycle. By reducing the need for long-distance shipping and cutting down on the carbon emissions associated with transportation, fully automated local production can lower the overall environmental footprint of garment manufacturing. However, the most significant benefit of nearshoring and automating is the increased overproduction, being reduced from 30% to 15%. Beyond this, the LCA also showed the significant ecological impact created by consumers, who’s buying, using and disposing behavior are crucial to the overall environmental impacts of the fashion industry.

From an economic perspective, the research indicates that investing in automation and relocating production makes sense under certain conditions. While the initial investment costs for fully automated systems are high, especially in high-wage countries, the long-term benefits of reduced labor costs, increased production efficiency, and shorter supply chains can outweigh these costs. Furthermore, automation can help companies meet growing consumer demand for sustainable and locally produced goods, providing a competitive advantage in the market.

However, fully automated production also entails several additional consequences. There are significant social implications, particularly concerning the displacement of workers in the garment industry. Automation could lead to job losses in regions where garment production is currently a major employer, necessitating strategies to manage these transitions, such as retraining programs and economic diversification initiatives. Additionally, companies may face technological challenges in developing and scaling automated systems that can handle a wide variety of fabrics and complex garment designs beyond basic products like T-Shirts.

Looking forward, the findings suggest several key trends and areas for further research. First, there is a need to explore more deeply the technological advancements required to make full automation feasible for various garment types beyond basic T-shirts. This includes refining robotic capabilities for handling delicate fabrics and more complex sewing tasks. Second, further investigation into the socioeconomic impacts of automation on labor markets, particularly in high-wage countries, is essential to develop strategies that mitigate negative consequences for workers(Introduction). Third, the alignment of automation strategies with emerging regulatory frameworks, such as the European Union’s Digital Product Passport, will be crucial for compliance and sustainability in the industry.

In conclusion, while the shift towards fully automated garment production presents both opportunities and challenges, it is clear that this transformation is necessary for the industry to meet future sustainability and economic goals. The research highlights the importance of a balanced approach that considers environmental benefits, economic viability, and social implications. Future work should continue to refine these models with more accurate data and expand the scope to include other textile products and regions, ultimately aiming to create a more sustainable and resilient fashion industry

6 References

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Appendix

World Trade Statistical Review 2023: Top 10 Exporters and Importers of Clothing, 2022

(Billion dollars and percentage)

	Value	Share in world exports/imports				Annual percentage change			
	2022	2000	2005	2010	2022	2010-22	2020	2021	2022
Exporters									
China (1)	182	18,2	26,6	36,6	31,7	3	-7	24	4
European Union	156	26,4	29,3	26,9	27,1	4	-8	20	4
Extra-EU exports	45	8,1	8,6	7,5	7,7	4	-13	14	4
Bangladesh (2)	45	2,6	2,5	4,2	7,9	10	-19	30	27
Vietnam (2)	35	0,9	1,7	2,9	6,1	11	-9	11	13
Türkiye	20	3,3	4,2	3,6	3,5	4	-6	22	6
India	18	3,0	3,1	3,2	3,1	4	-24	24	10
Indonesia	10	2,4	1,8	1,9	1,7	3	-12	24	8
Cambodia	9	0,5	0,8	0,9	1,6	10	-9	8	12
Pakistan	9	1,1	1,3	1,1	1,5	7	-3	37	5
United States of America	7	4,4	1,8	1,3	1,2	4	-19	27	17
Above 10	**492**	**62,8**	**73,1**	**82,6**	**85,5**	-	-	-	-
Importers									
European Union	215	32,7	37,4	37,6	35,5	4	-7	16	10
Extra-EU imports	111	16,4	19,4	21,2	18,4	3	-9	12	15
United States of America	116	33,1	28,7	22,1	19,2	3	-14	29	9
Japan	27	9,7	8,1	7,2	4,5	0	-12	1	2
United Kingdom	26	7,5	8,7	7,1	4,3	0	0	-12	12
Canada (3)	14	1,8	2,1	2,2	2,3	4	-7	15	15
Korea, Republic of	13	0,6	1,0	1,2	2,2	9	-12	17	15
China (1)	11	0,6	0,6	0,7	1,8	13	6	30	-12
Australia (3)	9	0,9	1,1	1,3	1,6	6	1	18	9
Switzerland	9	1,6	1,6	1,4	1,4	4	4	11	-3
Hong Kong, China	8	...	...	...	...	-6	-31	9	-11
Retained imports (2)	2	0,9	...	...	0,3	...	6	43	44
Above 10	**442**	**89,3**	**89,3**	**80,9**	**72,9**	-	-	-	-

(1) Includes significant shipments through processing zones.

(2) Secretariat estimates.

(3) Imports are valued f.o.b.

Foreign Agricultural Service/USDA: Cotton World Supply, Use and Trade 2019 – 2024

	2019/20	2020/21	2021/22	2022/23	Jan 2023/24	Feb 2023/24
Production						
China	5,977	6,445	5,835	6,684	5,987	5,987
India	6,205	5,987	5,291	5,726	5,443	5,443
Brazil	2,830	3,000	2,356	2,552	3,170	3,170
United States	4,336	3,181	3,815	3,150	2,707	2,707
Pakistan	1,350	980	1,306	849	1,459	1,459
Australia	136	610	1,274	1,263	1,110	1,045
Turkey	751	631	827	1,067	697	697
Other	4,347	3,984	4,222	4,021	4,068	4,056
Total	25,932	24,818	24,926	25,312	24,642	24,565
Domestic Use						
China	7,457	8,981	7,348	8,165	7,947	8,056
India	4,463	5,661	5,443	5,117	5,160	5,160
Pakistan	2,068	2,373	2,330	1,894	2,134	2,134
Bangladesh	1,546	1,894	1,916	1,676	1,698	1,698
Turkey	1,557	1,818	1,872	1,633	1,611	1,568
Vietnam	1,437	1,589	1,459	1,404	1,459	1,481
Brazil	588	675	718	697	718	718
Other	3,740	4,043	4,194	3,618	3,750	3,672
Total	22,856	27,035	25,281	24,204	24,478	24,486
Imports						
China	1,554	2,800	1,707	1,357	2,504	2,613
Bangladesh	1,676	1,829	1,840	1,524	1,633	1,633
Vietnam	1,411	1,587	1,444	1,409	1,459	1,481
Turkey	1,017	1,160	1,203	912	893	871
Pakistan	871	1,176	980	980	827	784
Indonesia	547	502	561	362	435	435
India	496	184	218	376	283	218
Other	1,295	1,355	1,404	1,287	1,340	1,302
Total	8,868	10,592	9,355	8,207	9,374	9,336
Exports						
United States	3,377	3,560	3,153	2,779	2,634	2,678
Brazil	1,946	2,398	1,682	1,449	2,504	2,439
Australia	296	344	779	1,343	1,252	1,230
India	697	1,348	815	239	348	348
Mali	256	152	283	163	245	250
Turkey	98	127	123	187	229	250
Benin	211	342	370	218	239	229
Other	2,091	2,397	2,198	1,668	1,922	1,910
Total	8,972	10,668	9,404	8,048	9,374	9,335
Ending Stocks						
China	7,859	8,120	8,288	8,143	8,668	8,677
India	3,415	2,578	1,828	2,574	2,792	2,727
Brazil	955	885	845	1,253	1,205	1,270
Australia	261	546	1,080	1,039	939	895
United States	1,579	686	882	925	631	610
Argentina	299	324	339	400	489	460
Uzbekistan	494	386	303	450	439	439
Other	4,312	3,387	3,075	3,279	3,209	3,145
Total	19,174	16,912	16,639	18,064	18,372	18,223

(in Metric tons)

Table 31: LCI Data for Scenario A – Raw Material Extraction

		Variable	Coefficient	Unit	Source
Cotton Cultivation	Inputs	Electricity, USA	733,705	kWh/ha	Cotton Incorporated, 2016, p. 35
		Diesel	59,923	l/ha	
		Seed-cotton	25,00	kg/ha	Chapter 5.2.4, Cotton Incorporated, 2020, p. 2; Sapkota *et al.*, 2023; Meyer and Dew, 2023
		Water, irrigation	4333,333	l/kg yield	
		Herbicides	1,868	kg/ha	United States Department of Agriculture, 2022, pp. 1–2
		Insecticides	0,448	kg/ha	
		Fungicides	0,00336	kg/ha	
		Harvest Aid, Defoliant	1,345	kg/ha	
		Phosphate	26,295	kg/ha	
		Potassium	31,933	kg/ha	
		Nitrogen	75,601	kg/ha	
	Outputs	Cotton, yield	0,713	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
Transport, Cotton yield	Inputs	Cotton, yield	0,713	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
		Distance to Gin	300	km	
	Outputs	Cotton, yield	1,258	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
Ginning	Inputs	Cotton, yield	1,258	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
		Electricity, USA	0,153	kWh/kg	Cotton Incorporated, 2016, p. 35
		Water	951,22	l/kg	(Cotton Incorporated, 2016, p. 69)
	Outputs	Cotton gin trash	10	%	(Egbuta *et al.*, 2019, p. 1)
		Cottonseeds	54	%	Chapter

	Cotton, fiber	36	%	**Fehler! Verweisquelle konnte nicht gefunden werden.**

		Variable	Coefficient	Unit	Source
Transport, Cotton yield	Input	Cotton, fiber	0,4052	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
		Distance to Yarn Manufacturing, truck, US	2100	kgkm	
		Distance to Yarn Manufacturing, containership, US-BG	18700	kgkm	Sea Distances, 2024
		Distance to Yarn Manufacturing, truck, BG	275	kgkm	Chapter
	Outputs	Cotton, fiber	0,4052	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
Spinning	Inputs	Cotton, fiber	0,4052	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
		Electricity, BG	0,226	kWh/kg	Uddin *et al.*, 2023, p. 4
		Natural gas	0,186	m³/kg	Uddin *et al.*, 2023, p. 5
	Outputs	Cotton yarn, waste	0,0202	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
		Cotton comber noil, by-product	0,0607	kg	Chapter 4.4.3
		Cotton yarn	0,3850	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
Knitting	Inputs	Cotton yarn	0,3850	kg	
		Electricity, BG	0,168	kWh/kg	(Uddin *et al.*, 2023)
		Natural gas	0,231	m³/kg	
	Outputs	Cotton yarn, waste	0,0385	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
		Cotton, fabric	0,3465	kg	

Dyeing & Finishing	Inputs	Cotton, fabric	0,3465	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
		Electricity, BG	2,209	kWh/kg	Mamun *et al.*, 2022, p. 516
		Natural gas	0,334	m³/kg	Uddin *et al.*, 2023, p. 4
		Dyes	0,041	kg/kg	Zhang *et al.*, 2015, p. 998
		Coal	2,371	kg/kg	
		Steam	1,301	kg/kg	
		Auxiliaries	1,108	kg/kg	
		Water	153,148	l/kg	
Dyeing & Finishing	Outputs	Water, waste	69,564	l/kg	Zhang *et al.*, 2015, p. 998
		Cotton, fabric, waste	0,0433	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
		Cotton, fabric	0,3395	kg	

Table 32: LCI Data for Scenario A – Shirt Manufacturing

Continuation to Table 32: LCI Data for Scenario A - Shirt Manufacturing

		Variable	Coefficient	Unit	Source
Dyeing & Finishing	Outputs	Water, waste	69,564	l/kg	Zhang *et al.*, 2015, p. 998
		Cotton, fabric, waste	0,0433	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
		Cotton, fabric	0,3395	kg	
Cutting	Inputs	Cotton, fabric	0,3395	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
		Electricity, BG	0,210	kWh/kg	Uddin *et al.*, 2023
	Outputs	Cotton, fabric, waste	0,0424	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
		Cotton, fabric	0,2971	kg	
Sewing	Inputs	Cotton, fabric	0,2971	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
		Electricity, BG	0,302	kWh/kg	Uddin *et al.*, 2023, p. 3
	Outputs	Cotton, fabric, waste	0,0371	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
		Cotton T-Shirt	0,260	kg	
Ironing & Finishing	Inputs	Cotton T-Shirt	0,260	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
		Electricity, BG	0,392	kWh/kg	Uddin *et al.*, 2023, p. 3
	Outputs	Cotton T-Shirt	1,3	pcs	**Fehler! Verweisquelle konnte nicht gefunden werden.**

Table 33: LCI Data for Scenario B – Raw Material Extraction

		Variable	Coefficient	Unit	Source
Cotton Cultivation	Inputs	Average yield	4960,80	kg/ha	(FAOSTAT, 2024)
		Electricity, TUR	5 308,36	kWh/ha	(Aytop, 2023, p. 7)
		Diesel	223,09	l/ha	
		Seed-cotton	29,16	kg/ha	
		Water, irrigation	2223,09	l/kg yield	
		Herbicides	1,60	kg/ha	
		Insecticides	2,07	kg/ha	
		Defoliant	1,15	kg/ha	
		Phosphate	95,84	kg/ha	
		Potassium	3,48	kg/ha	
		Nitrogen	287,19	kg/ha	
	Outputs	Cotton, yield	0,713	kg	(Aytop, 2023, p. 7)
Transport, Cotton yield	Inputs	Cotton, yield	0,713	kg	
		Distance to Gin	1210	km	Chapter 4.3.4
	Outputs	Cotton, yield	0,713	kg	Aytop, 2023, p. 7)
Ginning	Inputs	Cotton, yield	0,713	kg	
		Electricity, TUR	0,153	kWh/kg	(Funk and Harding, 2017, p. 156)
		Water	488	l/kg	(Aytop, 2023, p. 7)
	Outputs	Cotton gin trash	10	%	(Egbuta *et al.*, 2019)
		Cottonseeds	51	%	
		Cotton, fiber	39	%	

Table 34: LCI Data for Scenario B – Shirt Manufacturing

		Variable	Coefficient	Unit	Source
Transport, Cotton fiber	Input	Cotton, fiber	0,278	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
		Distance to Yarn Manufacturing	1590	kgkm	Chapter 4.3.4
	Outputs	Cotton, fiber	0,278	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
Spinning	Inputs	Cotton, fiber	0,278	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
		Electricity, TUR	3,847	kWh/kg	(Baydar *et al.*, 2015)
	Outputs	Cotton yarn, waste	0,028	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
		Cotton yarn	0,250	kg	

Knitting	Inputs	Cotton yarn	0,250	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
		Electricity, TUR	1,3889	kWh/kg	(Baydar *et al.*, 2015)
	Outputs	Cotton yarn, waste	0,008	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
		Cotton, fabric	0,247	kg	

Continuation to Table 20: LCI Data for Scenario B – Shirt Manufacturing

		Variable	**Coefficient**	**Unit**	**Source**
Dyeing & Finishing	Inputs	Cotton, fabric	0,247	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
		Electricity, TUR	0,845	kWh/kg	(Baydar *et al.*, 2015)
		Dyes	0,049	kg/kg	
		Natural gas	7,429	kWh/kg	
		Steam	7,429	kg/kg	
		Auxiliaries	13,100	kg/kg	
		Water	177,300	l/kg	
	Outputs	Water, waste	175,855	l/kg	(Baydar *et al.*, 2015)
		Cotton, fabric, waste	0,005	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
		Cotton, fabric	0,238	kg	
Transport, Cotton fabric	Inputs	Cotton, fabric	0,238	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
		Distance to Making-up, Truck	1771	kgkm	Google Maps
	Outputs	Cotton, fabric	0,3395	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
Cutting	Inputs	Cotton, fabric	0,3395	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
		Electricity, AUT	0,239	kWh/kg	Silana
	Outputs	Cotton, fabric, waste	0,0424	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
		Cotton, fabric	0,2971	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
Sewing	Inputs	Cotton, fabric	0,2971	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**
	Outputs	Electricity, AUT	0,553	kWh/kg	Silana
		Cotton, fabric, waste	0,0371	kg	Silana

	Cotton T-Shirt	0,260	kg	**Fehler! Verweisquelle konnte nicht gefunden werden.**

Table 35: LCI Data for Scenario A and Scenario B – Retail

		Variable	Coefficient	Unit	Source
Transport, T-Shirt (to Store)	Inputs	Cotton T-Shirt	1,3	pcs	Chapter 4.3.4
		Distance to Retail, truck, BG	275	kgkm	
		Distance to Retail, containership, BG-DE	30375	kgkm	Routescanner
		Distance to Retail, truck, DE	500	kgkm	Assumption, Umweltbundesamt, 2022
	Outputs	Cotton T-Shirt	1,3	pcs	Chapter 4.3.4
Retail	Inputs	Cotton T-Shirt	1,3	pcs	Chapter 4.3.4
	Outputs	Cotton T-Shirt	1	pcs	Chapter 4.3.4
		Cotton T-Shirt, overproduced	0,3	pcs	
Transport, T-Shirt (to Customer)	Inputs	Cotton T-Shirt	1	pcs	Chapter 4.3.4
		Distance to customer, onsite, bus	0,155	person*km	Lehmann *et al.*, 2019, p. 33; Handelsdaten, 2024
		Distance to customer, onsite, car	5,067	km	
		Distance to customer, onsite, public transport	0,110	person*km	
		Distance to customer, online, van	0,148	kgkm	
		Distance to customer, truck	50,598	kgkm	
	Outputs	Cotton T-Shirt	1	pcs	Chapter 4.3.4

Table 36: LCI Data for Scenario A and Scenario B – Use Phase

		Variable	Coefficient	Unit	Source
Washing	Inputs	Cotton T-Shirt	1	pcs	Chapter 4.3.4
		Washing machine	2,49	loads/pcs	Lehmann *et al.*, 2019, p. 30
		Water	51,4	l/load	
		Electricity, GER	1,470	kWh/load	
		Detergent, liquid	0,056	kg/load	
	Outputs	Water, waste	50,53	l/load	Lehmann *et al.*, 2019, p. 30
		Cotton T-Shirt, wet	1	pcs	Chapter 4.3.4
Drying	Inputs	Cotton T-Shirt, wet	1	pcs	Chapter 4.3.4
		Dryer	44	loads/pcs	Lehmann *et al.*, 2019, p. 31
		Electricity, GER	1,483	kWh/load	
	Outputs	Water, waste	0,044	l/load	Lehmann *et al.*, 2019, p. 31
		Cotton T-Shirt	1	pcs	Chapter 4.3.4
Use	Inputs	Cotton T-Shirt	1	pcs	Chapter 4.3.4
	Outputs	Cotton T-Shirt	1	pcs	Chapter 4.3.4
		Cotton T-Shirt, EoL	1	pcs	

Table 37: LCI Data for Scenario A and Scenario B – Disposal

		Variable	Coefficient	Unit	Source
Transport, T-Shirt (to EoL)	Inputs	Cotton T-Shirt, EoL	1	pcs	Chapter 4.3.4
		Distance to EoL, car	1,476	km	Lehmann *et al.*, 2019, p. 35
		Distance to EoL, bus	0,045	person*km	
		Distance to EoL, public transport	0,032	person*km	
		Distance to EoL, waste transporter	6,006	person*km	
	Outputs	Cotton T-Shirt, EoL	1	pcs	Chapter 4.3.4
Disposal	Inputs	Cotton T-Shirt, EoL	1	pcs	Chapter 4.3.4
	Outputs	Cotton T-Shirt, landfilled	52	%	Lehmann *et al.*, 2019, p. 72
		Cotton T-Shirt, incinerated		%	
		Cotton T-Shirt, downcycled		%	

Table 38: Case Study – LCI Mappings with ecoinvent (Scenario A)

From	To
Carbon dioxide	Carbon dioxide, fossil (emissions to air, unspecified) (ecoinvent-3.9.1)
Coal	Coke (GLO, market for coke) (ecoinvent-3.9.1)
Coal, cinder	Coal slurry (GLO, market for coal slurry) (ecoinvent-3.9.1)
Cotton, Fabric, waste	Waste yarn and waste textile (GLO, market for waste yarn and waste textile) (ecoinvent-3.9.1)
Cotton, T-Shirt, incinerated	Waste textile, soiled (RoW, treatment of waste textile, soiled, municipal incineration) (ecoinvent-3.9.1)
Cotton T-Shirt, landfilled	Waste yarn and waste textile (RoW, treatment of waste yarn and waste textile, unsanitary landfill) (ecoinvent-3.9.1)
Cotton yarn, waste	Waste yarn and waste textile (GLO, market for waste yarn and waste textile) (ecoinvent-3.9.1)
Cottonseeds, by-product	Cotton seed oil, refined (US, cottonseed oil refinery operation) (ecoinvent-3.9.1)
Defoliant	Sodium chloroacetate (GLO, sodium chloroacetate production) (ecoinvent-3.9.1)
Detergent, liquid	Ammonia, anhydrous, liquid (RER, cocamide diethanolamine production) (ecoinvent-3.9.1)
Diesel, US	Diesel, burned in agricultural machinery (GLO, diesel, burned in agricultural machinery) (ecoinvent-3.9.1)
Distance to customer, in-store, bus	Transport, regular bus (GLO, market for transport, regular bus) (ecoinvent-3.9.1)
Distance to customer, in-store, car	Transport, passenger car (RoW, transport, passenger car) (ecoinvent-3.9.1)
Distance to customer, in-store, public transport	Transport, tram (GLO, market for transport, tram) (ecoinvent-3.9.1)
Distance to customer, online, lkw	Transport, freight, lorry, unspecified (RoW, transport, freight, lorry, all sizes, EURO3 to generic market for transport, freight, lorry, unspecified) (ecoinvent-3.9.1)
Distance to customer, online, van	Transport, freight, light commercial vehicle (Europe without Switzerland, transport, freight, light commercial vehicle) (ecoinvent-3.9.1)
Distance to EoL, bus	Transport, regular bus (GLO, market for transport, regular bus) (ecoinvent-3.9.1)
Distance to EoL, car	Transport, passenger car (RoW, transport, passenger car) (ecoinvent-3.9.1)
Distance to EoL, public transport	Transport, tram (GLO, market for transport, tram) (ecoinvent-3.9.1)
Distance to EoL, waste transporter	Transport, freight, lorry 28 metric ton, fatty acid methyl ester 100%) (ecoinvent-3.9.1)
Distance to Gin	Transport, freight, lorry, unspecified (RoW, transport, freight, lorry, all sizes, EURO3 to generic market for transport for transport, freight, lorry, unspecified) (ecoinvent-3.9.1)
Distance to Retail, sea	Transport, freight, sea, container ship (GLO, market for transport, freight, sea, container ship) (ecoinvent-3.9.1)

Continuation to Table 26: Case Study: LCI Mappings with ecoinvent (Scenario A)

From	To
Distance to Retail, truck, BG	Transport, freight, lorry, unspecified (RoW, transport, freight, lorry, all sizes, EURO3 to generic market for transport for transport, freight, lorry, unspecified) (ecoinvent-3.9.1)
Distance to Retail, truck, DE	Transport, freight, lorry 16-32 metric ton, EURO3 (RoW, transport, freight, lorry 16-32 metric ton, EURO3) (ecoinvent-3.9.1)
Distance to Yarn, containership, US-BG	Transport, freight, sea, container ship (GLO, market for transport, freight, sea, container ship) (ecoinvent-3.9.1)
Distance to Yarn, truck, BG	Transport, freight, lorry, unspecified (RoW, transport, freight, lorry, all sizes, EURO3 to generic market for transport for transport, freight, lorry, unspecified) (ecoinvent-3.9.1)
Distance to Yarn, truck, US	Transport, freight, lorry, unspecified (RoW, transport, freight, lorry, all sizes, EURO3 to generic market for transport for transport, freight, lorry, unspecified) (ecoinvent-3.9.1)
Dyes	Batch dyeing, fibre, cotton (GLO, market for batch dyeing, fibre, cotton) (ecoinvent-3.9.1)
Electricity, BG	Electricity, medium voltage (BG, electricity, medium voltage, residual mix) (ecoinvent-3.9.1)
Electricity, DE	Electricity, medium voltage (DE, electricity, medium voltage, residual mix) (ecoinvent-3.9.1)
Electricity, USA	Electricity, medium voltage (RNA, market group for electricity, medium voltage)
Fertilizer	Inorganic nitrogen fertiliser, as N (GLO, nutrient supply from ammonium chloride) inorganic phosphorus fertilizer, as P205 (RNA, nutrient supply from ammonium nitrate phosphate) Inorganic potassium fertilizer, as K2O (RNA, nutrient supply from potassium nitrate) Potassium sulfate (RoW, potassium sulfate production)
Fly ash	Fly ash and scrubber slufge (CG, market for fly ash and scrubber sludge) (ecoinvent-3.9.1)
Fungicides	Captan (GLO, market for captan)
Herbicides	Glyphosate (GLO, market for glyphosate) mecoprop (GLO, market for mecoprop)
Natural gas	Electricity, high voltage (BG, electricity production, natural gas, conventional power plant) (ecoinvent-3.9.1)
Phosphate	Ammonium nitrate phosphate (RoW, ammonium nitrate phosphate production) (ecoinvent-3.9.1)
Seed-cotton	Seed-cotton (GLO, market for seed-cotton) (ecoinvent-3.9.1)
Steam	Steam, in chemical industry (RoW, market for steam, in chemical industry) (ecoinvent-3.9.1)
Sulfur dioxide	Sulfur (emissions to soil, agricultural) (ecoinvent-3.9.1)
Water	Water, unspecified natural origin (resources from water, unspecified) (ecoinvent-3.9.1)

Table 39: Case Study – LCI Mappings with ecoinvent (Scenario B)

From	To
Auxiliaries	Acetid acid, without water, in 98% solution state (RER, oxidation of butane) calcium chloride (RER, soda production, solvay process) cationic resin (RER, market for cationic resin) hydrogen peroxide, without water, in 50% solution state (RER, hydrogen peroxide production, product in 50% solution state) Neutralising agent, sodium hydroxide-equivalent (GLO, sodium hydroxide to generic market for neutralizing agent) Non-iconic surfactant (GLO, non-ionic surfactant production, ethylene oxide derivate) Salt (GLO, salt production from seaater, evaporation pond) Silicon carbide (RER, silicon carbide production) Soap (RER, soap production) Soda ash, light (GLO, market for soda ash, light) Sodium silver thiosulfate (GLO, market for sodium silver thiosulfate)
Coal	Coke (GLO, market for coke) (ecoinvent-3.9.1)
Cotton, Fabric, waste	Waste yarn and waste textile (GLO, market for waste yarn and waste textile) (ecoinvent-3.9.1)
Cotton, T-Shirt, incinerated	Waste textile, soiled (RoW, treatment of waste textile, soiled, municipal incineration) (ecoinvent-3.9.1)
Cotton T-Shirt, landfilled	Waste yarn and waste textile (RoW, treatment of waste yarn and waste textile, unsanitary landfill) (ecoinvent-3.9.1)
Cotton yarn, waste	Waste yarn and waste textile (GLO, market for waste yarn and waste textile) (ecoinvent-3.9.1)
Cottonseeds, by-product	Cotton seed oil, refined (US, cottonseed oil refinery operation) (ecoinvent-3.9.1)
Defoliant	Sodium chloroacetate (GLO, sodium chloroacetate production) (ecoinvent-3.9.1)
Detergent, liquid	Ammonia, anhydrous, liquid (RER, cocamide diethanolamine production) (ecoinvent-3.9.1)
Diesel, TUR	Diesel, burned in agricultural machinery (GLO, diesel, burned in agricultural machinery) (ecoinvent-3.9.1)
Distance to customer, in-store, bus	Transport, regular bus (GLO, market for transport, regular bus) (ecoinvent-3.9.1)
Distance to customer, in-store, car	Transport, passenger car (RoW, transport, passenger car) (ecoinvent-3.9.1)
Distance to customer, in-store, public transport	Transport, tram (GLO, market for transport, tram) (ecoinvent-3.9.1)
Distance to customer, online, lkw	Transport, freight, lorry, unspecified (RoW, transport, freight, lorry, all sizes, EURO3 to generic market for transport, freight, lorry, unspecified) (ecoinvent-3.9.1)
Distance to customer, online, van	Transport, freight, light commercial vehicle (Europe without Switzerland, transport, freight, light commercial vehicle) (ecoinvent-3.9.1)
Distance to EoL, bus	Transport, regular bus (GLO, market for transport, regular bus) (ecoinvent-3.9.1)
Distance to EoL, car	Transport, passenger car (RoW, transport, passenger car) (ecoinvent-3.9.1)

Continuation to Table 40: Case Study – LCI Mappings with ecoinvent (Scenario B)

From	To
Distance to EoL, public transport	Transport, tram (GLO, market for transport, tram) (ecoinvent-3.9.1)
Distance to Gin	Transport, freight, lorry, unspecified (RoW, transport, freight, lorry, all sizes, EURO3 to generic market for transport for transport, freight, lorry, unspecified) (ecoinvent-3.9.1)
Distance to Retail, truck, DE	Transport, freight, lorry 16-32 metric ton, EURO3 (RoW, transport, freight, lorry 16-32 metric ton, EURO3) (ecoinvent-3.9.1)
Distance to Yarn Manufacturing	Transport, freight, lorry, unspecified (RoW, transport, freight, lorry, all sizes, EURO3 to generic market for transport for transport, freight, lorry, unspecified) (ecoinvent-3.9.1)
Dyes	Batch dyeing, fibre, cotton (GLO, market for batch dyeing, fibre, cotton) (ecoinvent-3.9.1)
Electricity, AT	Electricity, medium voltage (AT, market for electricity, medium voltage) (ecoinvent-3.9.1)
Electricity, DE	Electricity, medium voltage (DE, electricity, medium voltage, residual mix) (ecoinvent-3.9.1)
Electricity, TUR	Electricity, medium voltage (RER, market group for electricity, medium voltage)
Fungicides	Captan (RER, captan production) (ecoinvent-3.9.1)
Herbicides	Glyphosate (GLO, market for glyphosate) mecoprop (GLO, market for mecoprop)
Natural gas	Electricity, high voltage (TR, electricity production, natural gas, conventional power plant) (ecoinvent-3.9.1)
Phosphate	Ammonium nitrate phosphate (RoW, ammonium nitrate phosphate production) (ecoinvent-3.9.1)
Seed-cotton	Seed-cotton (GLO, market for seed-cotton) (ecoinvent-3.9.1)
Steam, Natural Gas	Steam, in chemical industry (RER, market for heat, from steam, in chemical industry) (ecoinvent-3.9.1)
Sulfur dioxide	Sulfur (emissions to soil, agricultural) (ecoinvent-3.9.1)
Water	Water, unspecified natural origin (resources from water, unspecified) (ecoinvent-3.9.1)

Table 40: LCIA – Specific impact for life cycle stages of Scenario A (EF3.1)

Impact Category	WSF	LU	MM	FO	AP	EP	MAETP	FAETP	ET	IO	POCP	HT	GWP
Raw Material Extraction	1,337	0,000	3,409	0,001	0,004	0,001	0,000	5,310	0,024	0,001	0,000	0,000	0,283
Shirt Manufacturing	6,711	0,000	22,746	0,010	0,022	0,002	0,000	4,936	0,414	0,007	0,000	0,000	3,612
Distribution	2,167	0,000	6,336	0,004	0,011	0,001	0,000	3,764	0,009	0,004	0,000	0,000	0,481
Use Phase	1,508	0,000	12,026	0,002	0,005	0,001	0,000	1,951	0,150	0,001	0,000	0,000	0,785
Disposal	0,575	0,000	1,600	0,001	0,003	0,000	0,000	0,979	0,002	0,001	0,000	0,000	0,317
Total	12,298	0,000	46,118	0,018	0,044	0,005	0,001	16,938	0,600	0,013	0,000	0,000	5,478

Table 41: LCIA – Specific impact for life cycle stages of Scenario B (EF3.1)

Impact Category	WSF	LU	MM	FO	AP	EP	MAETP	FAETP	ET	IO	POCP	HT	GWP
Raw Material Extraction	0,135	1,299	0,000	2,631	0,001	0,004	0,001	0,000	2,819	0,010	0,001	0,000	0,217
Shirt Manufacturing	0,127	1,086	0,000	12,345	0,003	0,004	0,000	0,000	2,420	0,032	0,002	0,000	0,973
Distribution	0,043	2,068	0,000	5,421	0,002	0,005	0,000	0,000	3,314	0,008	0,002	0,000	0,407
Use Phase	0,138	1,508	0,000	12,026	0,002	0,005	0,001	0,000	1,951	0,150	0,001	0,000	0,785
Disposal	0,012	0,550	0,000	1,427	0,000	0,001	0,000	0,000	0,884	0,002	0,001	0,000	0,222
Total	0,455	6,512	0,000	33,850	0,007	0,019	0,002	0,001	11,389	0,202	0,007	0,000	2,604