Optimizing Water Impact in Textile Supply Chains:
The Case of Hemp as a Textile Fiber

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I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the *Universidade de Lisboa*.

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As I present my master's dissertation, the culmination of my academic journey in Industrial Engineering and Management, I look back on the challenges I overcame, and would like to take this opportunity to thank and acknowledge everyone that, at any point in time, helped me to do so.

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Abstract

The projected expansion of the global middle class, particularly in Asia, is poised to increase apparel production. In a world where the patterns of consumption have already instigated a global water crisis, this projection can significantly aggravate water scarcity, given the textile sector's large dependency on water. To face growing environmental concerns, the industry has been exploring hemp as a more sustainable fiber than cotton.

This work presents a multi-objective mixed integer linear programming model as a decision support tool for the design and planning of a sustainable supply chain, integrating decisions concerning suppliers, production and storage facilities' selection; purchase levels; transportation network and product-mix. The objective functions address the triple bottom line approach: economic, through Net Present Value (NPV); environmental through the supply chain's water impact, which considers raw materials' water footprint, operations' water consumption and the water stress level of the regions where these activities occur; social, through employment generation. The ε-constraint method was used to solve the multi-objective optimization. Other environmental impacts were also analyzed and a stochastic approach was employed to face demand uncertainty.

The model was applied to an apparel company and a set of recommendations was proposed to reduce the water impact both in a network that only trades cotton jeans and one that also trades jeans partly composed of hemp. It was found that introducing hemp in the network can improve the NPV by 5.36×10^5 currency units, the water consumption by 3.60×10^6 m^3 and social and environmental benefits by 5% and 3%, respectively.

Keywords

Sustainability, Water Scarcity, Supply Chain Design and Planning, Multi-objective, Textile Industry, Hemp

Resumo

O crescimento previsto da classe média global, particularmente na Ásia, irá aumentar a produção de vestuário. Esta projeção pode vir a agravar significativamente a escassez de água, considerando a dependência da indústria têxtil a este recurso. Com crescentes preocupações ambientais, a indústria tem vindo a explorar o cânhamo como uma matéria-prima mais sustentável que o algodão.

Este trabalho apresenta um modelo de programação linear multiobjectivo como ferramenta de apoio à decisão para o planeamento de cadeias de abastecimento sustentáveis, integrando decisões como a seleção de fornecedores, de instalações de produção e de armazenamento; níveis de compra; rede de transporte e tipo de produtos a fabricar. As funções objetivo abordam os três pilares da sustentabilidade: económico, através do Valor Presente Líquido; ambiental, através do impacto hídrico da cadeia, considerando a pegada hídrica das matérias-primas, o consumo de água das operações e o stress hídrico das regiões onde estas ocorrem; social, através da criação de emprego. O método *ε-constraint* foi usado para a otimização multiobjectivo. Outros impactos ambientais também foram analisados e uma abordagem estocástica foi empregue para confrontar a incerteza na procura.

O modelo foi aplicado a uma empresa de vestuário e foram propostas recomendações para reduzir o impacto hídrico, numa rede que apenas comercializa *jeans* de algodão e numa que também comercializa *jeans* parcialmente feitas com cânhamo. Verificou-se que a incorporação de cânhamo origina uma melhoria económica de 5.36×10^5 unidades monetárias, melhoria no consumo de água de 3.60×10^6 m^3 e nos benefícios sociais e ambientais de 5% e 3%, respetivamente.

Palavras-chave

Sustentabilidade, Escassez de Água, Planeamento de Cadeias de Abastecimento, Multiobjectivo, Indústria Têxtil, Cânhamo

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List of Abbreviations

BOM	Bill Of Materials
CU	Currency Units
FAB	Fabric
FP	Final Product
GDP	Gross Domestic Product
GP	Goal Programming
LCA	Life Cycle Assessment
MILP	Mixed Integer Linear Programming
MOVDO	Multi-Objective Vibration Damping Optimization
NPV	Net Present Value
PPP	Purchasing Parity Power
RM	Raw Material
SSCM	Sustainable Supply Chain Management
UN	United Nations
WF	Water Footprint
WFA	Water Footprint Assessment

1- Introduction

This chapter aims to introduce the work carried out and it is divided in three sections. Section 1.1 describes the motivation behind the development of this work, Section 1.2 highlights the dissertation's main objectives and Section 1.3 its outline.

1.1 Problem motivation

The present work was primarily instigated by the prevailing global water crisis. The problem motivation can be segmented into four other key domains that are intimately related to this initial concern: the expected growth of the middle class, the expected economic shift towards Asia, the water impact of the textile industry and the ongoing quest for more water-efficient raw materials in this industry. Each one of these topics will be further discussed ahead.

The global water crisis

Over the past few decades, the world has been stage to an increasing, and unprecedented, over-exploitation of freshwater resources. The total quantity of renewable water available for human and natural consumption represents a sheer 0.19% of the total amount of water present in our planet, as seen in Figure 1, turning this excessive consumption into a source of profound concern.

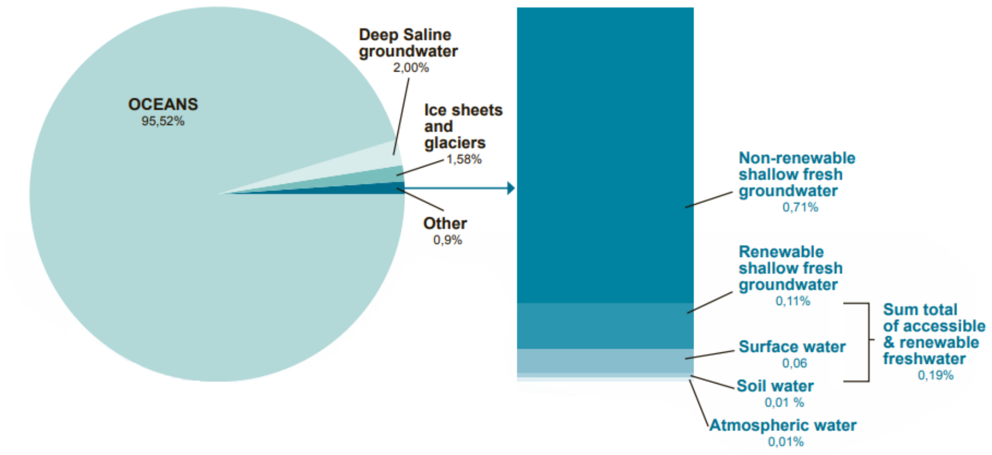

Figure 1: Composition of Earth's accessible freshwater available for use. Adapted from: Morgan, Luthra, et al. (2022).

The witnessed population growth and the economic move towards a more resource-intensive pattern of consumption have led global water withdrawals to rise by almost 600% since 1900 (Ritchie and Roser, 2017). This increasing demand for water both from communities and businesses, allied with the already shortened water resources, from decades of unsustainable usage, have resulted in many basins currently experiencing annual withdrawals far above its sustainable limits (Morgan, Luthra, et al., 2022). Globally, 72% of these water withdrawals are used in the agricultural sector, 16% in households and services and 12% in industries (UN-Water, 2021).

Future trends: the emerging middle class and the economic shift towards Asia.

According to multiple reports, the rapid expansion of the "global middle class" is an emerging trend to be mindful of, with some projections estimating that it will more than double from 1.8 billion to 5 billion, from 2009 to 2030 (ESPAS, 2015).

Although these figures represent projections, recent reports support this growth rate. In September 2018, there were approximately 3.8 billion people, reaching 50% of the world population at the time, that were considered "middle class" or "rich", while the other half of the population lived in poor or vulnerable-to-poor households (Kharas & Hamel, 2018).[1] In its status as an economic group, the definition for middle class can vary greatly, according to factors such as income distribution, purchasing power and economic stability. Nevertheless, despite these variations, researchers are in consensus on the substantial growth this group has been experiencing and will continue to do so (Donmaz et al., 2017; European Parliamentary Research Service, 2018).

A more broadly agreed-upon definition is obtained when referring to the middle class as a social group, which expresses that in the absence of severe financial hardships, the consumption patterns and lifestyles begin to change. As projected by Never (2020), the consumption of the emerging middle classes will be marked by a higher demand for diversified products and services that support a standard of living beyond the basic needs.

The expected geographical distribution of this global middle class is represented in Figure 2.

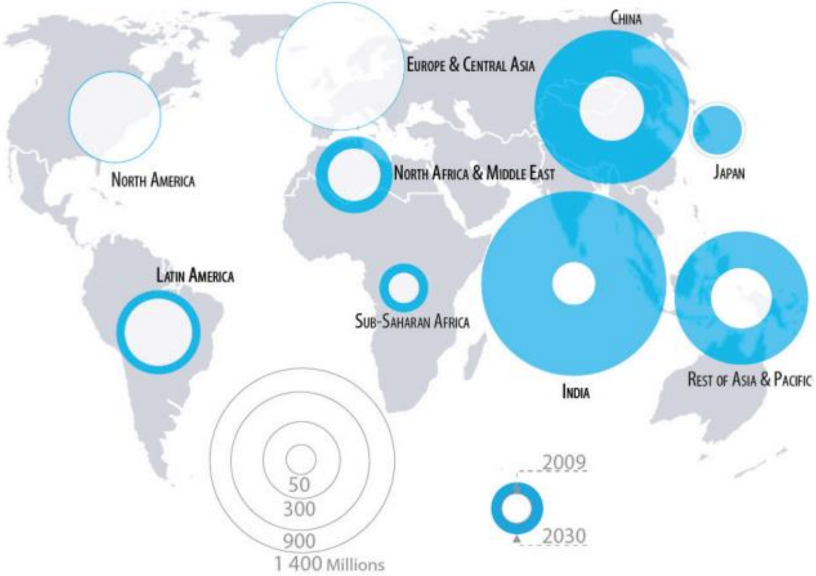

Figure 2: Expected middle class growth from 2009 to 2030. Adapted from: ESPAS (2015).

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[1] These statistics are based on a classification of middle class that assumes a household expenditure of $11-110 per capita per day in 2011 purchasing power parity (PPP).

Alongside the global projections made, it is also forecasted that the growth will be majorly concentrated in Asia, which is expected to hold 66% of the total world's middle class (ESPAS, 2015).

By 2030, it is expected that China and India will assume a leading position in this matter. The former could have more than 70% of its population classified as middle class, with a consumption of nearly $10 trillion, and India could become the world's largest middle class consumer market. The expansion of this market will also play a key role within developing countries with emerging economies, that could register annual growth rates higher than 6%, contrasting with the projected annual growth of 0.5%-1% in the developed countries (World Bank, 2018). These projections place substantial momentum in Asia, where multiple companies, seeking to capitalize on this expansion, are positioning their businesses to be closer to their customers.

As global demand shifts to China, India and other developing countries, more of their domestic production is now also being consumed internally, instead of being exported. Between 2007 and 2017, the exports share in labor-intensive and global innovations value chains of China dropped from 29% to 15% and of other emerging economies, from 33% to 27% (McKinsey & Company, 2019).

This phenomenon is reflected in the apparel industry, a highly labor-intensive industry. As a result of the growing incomes and larger demand, the percentage of exports fell from 35% to 17% from 2002 to 2017, in India, in favor of local consumption where the average spending on apparel and footwear increased $24 per person in 10 years (McKinsey & Company, 2019).

Nevertheless, it is important to recognize that while there is discourse surrounding a "global" middle class, this does not presuppose the homogeneity of this group. The discrepancy in purchasing powers between countries will persist and, in fact, emerge as a significant barrier when entering the Asian market. The market's sheer size and extreme consumer diversity makes it exceptionally hard to forecast demand and consumption patterns for each unique segment. Companies must seek innovative strategies that account for the different consumer and economic profiles, as well as their distinct purchasing powers in order to offer products that cater to different preferences and multiple price points (McKinsey & Company, 2015). Moreover, companies require an efficient supply chain management to navigate this new market, as the continent's topography, different regulations and infrastructure disparities can easily become complex challenges.

The textile industry and its water impact

The textile industry is a highly globalized industry that took a central role in the economic development of many countries. While clothing is still a basic need, it has evolved far beyond its original purpose, extending its influence to become an integral part of fashion statements and an important means for self-expression.

In 2021, the global textile and apparel market was valued at, approximately, $2.5 trillion and is expected to grow at an annual rate of 3.88% from 2022 to 2030 (Coherent Market Insights, 2022). It is also the seventh most traded industry in the world (UN Comtrade, 2021).

The globalization of the sector enabled a more cost-effective production, since companies benefited from outsourcing their manufacturing needs to countries with lower, therefore more attractive, labor costs. Globalization also facilitated the emergence of fast fashion, a new business model that allowed apparel companies to capitalize on the rapid turnover of fashion trends and the growing patterns of consumption. This phenomenon required a highly responsive and efficient supply chain, as well as a significant increase in the levels of production.

In more recent years, the decrease of Chinese reliance on textile and apparel production has benefited other developing Asian countries where the production has been diversified to. As per ILO (2021), in 2019 Bangladesh and Vietnam's combined share of apparel and footwear global exports matched 37% of China's.

The generation of production hotspots, namely in Bangladesh, Vietnam and Pakistan, spawned economies heavily dependent on the apparel sector. Although there is still an urgent need for more effective legislations regarding inequalities and working conditions in many of these countries, the sector's economic development enabled the creation of millions of jobs, which supported several low-income nations in achieving a middle-income status (Sharpe, 2021).

Regrettably, the industry is also one of the largest consumers of freshwater, with a consumption of approximately 79 billion cubic meters of freshwater per year (Environmental Audit Committee, 2019). The sector is facing tremendous resource challenges as water is needed at every stage of the value chain, from the cultivation of the raw materials up until the final disposal of the product. Furthermore, driven by heightened awareness of environmental concerns, segments of buyers are currently demanding the textile industry to incorporate more sustainable practices into their supply chains (Raian et al., 2022).

The prevalence of garment production hotspots combined with the water-intensive practices of the industry have contributed to the water stress affecting these regions, which, according to Morgan et al. (2022), are subject to significant water risks such as flooding, pollution and water availability. In addition, with the growing pressure to design sustainable supply chains, the textile industry has emerged as a focal point for investigation.

Hemp's potential as a water-efficient textile raw material

For decades now, cotton has firmly held its position as one of the most widely used raw materials in the textile and apparel industry (Gedik and Avinc, 2020). Cotton constituted 21% of the global fiber production of 2021, and in 2022 its production reached 25.2 million tons (Lenzing Group, 2022).

Meanwhile, according to Gedik and Avinc (2020), the consumption of insecticide and pesticide in cotton's cultivation represents approximately one-fourth and one-tenth of the world's production, respectively. In addition, cotton is characterized as a highly water-intensive crop (Fernández-Stark et al., 2022). This was evidenced by Chapagain et al. (2006) that estimated the consumption of cotton products to account for 2.6% of the global water footprint. Other studies have also found that the intensive use of water resources is ecologically unsustainable in many cotton-producing regions (Bevilacqua et al., 2014).

Figure 3 displays the exposure to physical water risk of cotton production regions.

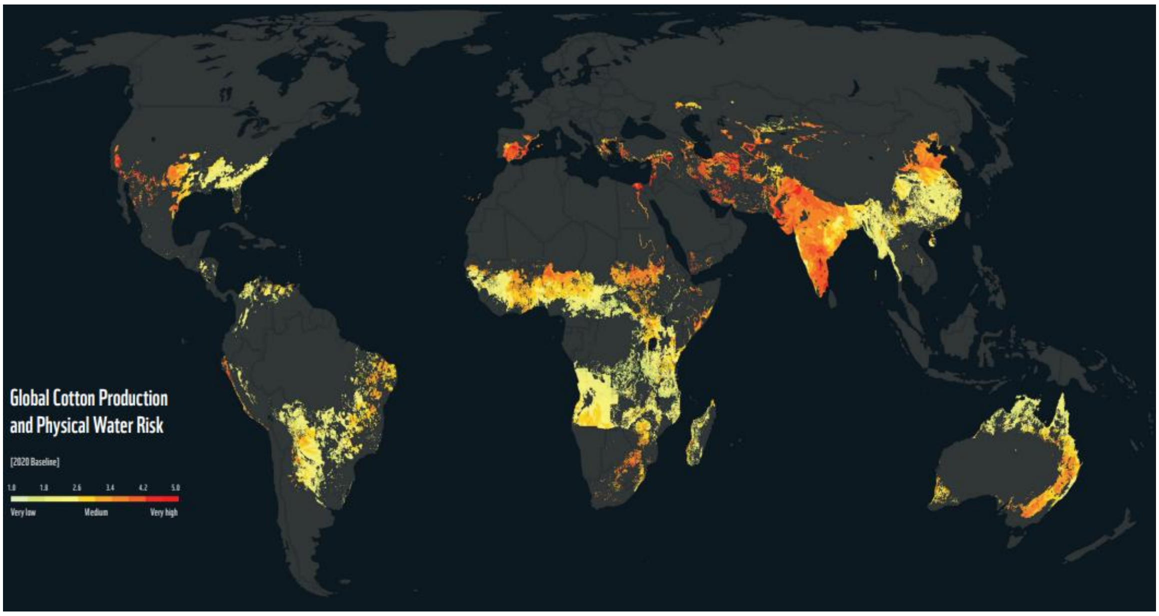

Figure 3: Global cotton production regions and its exposure to physical water risk. Adapted from: Morgan, Camargo, et al. (2022).

To address these environmental concerns, the shift towards more sustainable fibers has been growing in the textile and apparel industry (Fernández-Stark et al., 2022), with the raw material hemp being praised for his sustainability potential in the sector.

This work was motivated by the need to address all the issues described thus far, which are tightly interconnected and have the potential to intensify the depletion of our already scarce freshwater resources. Figure 4 illustrates these connections.

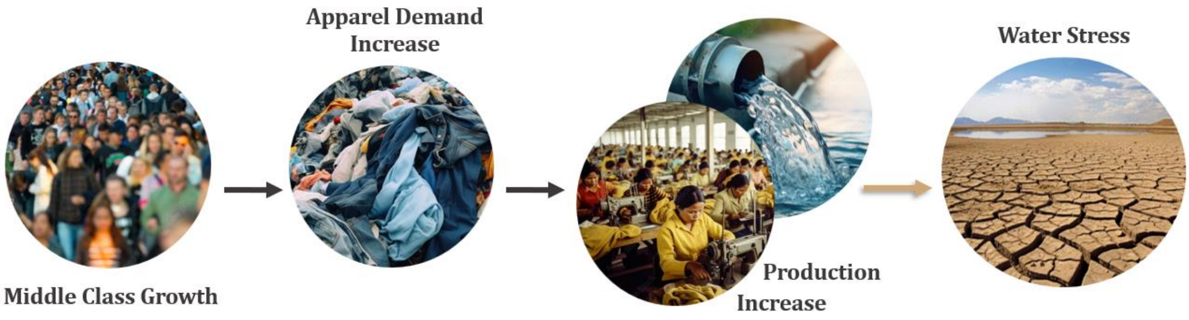

Figure 4: How the growth of the middle class can impact water stress. Images source: (*Adobe Images*, 2023)

The rise of the middle class, characterized by the changing consumption patterns, will instigate a rise in various products' demand, namely apparel. This higher demand will lead to an increase in textile and apparel production which, as previously established, is a major consumer of freshwater resources. Furthermore, the concentration of production in Asia, which is also projected to house a significant share of the global middle class, is poised to amplify water stress levels in these production hotspots.

To prevent this chain of events from further aggravating the global water crisis, it is of extreme importance that the design and planning of textile supply chains considers the water implications caused by the network. Additionally, as it was mentioned before, the ongoing research for less water-intensive raw materials, such as hemp, also constitutes an important strategy to deal with the sector's dependency on water and to mitigate the impact of the events illustrated in Figure 4.

1.2 Dissertation's objectives

The objective of the present work is to contribute to the body of research concerning the design and planning of sustainable supply chain networks, with consideration for the global water crisis and its implications on industries. It intends to delve into the textile and apparel industry, and its large water-demanding practices, and support the creation of sustainable supply chains within the sector, from a strategic level perspective. Furthermore, it seeks to provide insights that can help with the industry's shift towards more sustainable fibers by analyzing the economic, environmental and social implications of incorporating hemp as a raw material in a textile supply chain.

This work intends to explore and give answer to two research questions:

Research Question 1: How can supply chains' network design be adjusted to face the increasing depletion of freshwater resources and expected increase of its requirements?

As it was previously established, it is expected that the middle class growth will increase the pressure exerted on the available freshwater resources. Therefore, this research question emerges as a starting point to provide solutions for how supply chains should adjust their networks to face this emerging trend and other related ones, already discussed.

Research Question 2: What impacts can the introduction of hemp as a raw material have in the textile industry?

Given the textile and apparel industry's efforts to adopt more eco-friendly fibers, this research question aims to give insights into the impacts of introducing hemp as a raw material in a textile supply chain.

Through the development of an optimization model, applied to a case study of an apparel company, for validation purposes, it is expected that valuable managerial insights can be offered to decision-makers. Insights related to decisions that concern the selection of the supply chain's entities as well as production, inventory and transportation necessities. Examining the main differences between considering a deterministic versus a stochastic demand is also among the goals of the case study analysis.

The model is driven by three objective functions, each one representing one of the three sustainability pillars. The economic performance is optimized through the Net Present Value (NPV), the social benefit is measured by the creation of employment within the supply chain and the environmental pillar is addressed through the water impact of the supply chain. The goal is to measure this water impact by taking into account the supply chain’s water consumption requirements as well as the level of water stress in the regions where the entities of the network are located. It is also within the expectations of this work to address other environmental considerations of the supply chain.

The research methodology adopted consists of the following steps:

Problem motivation and contextualization – Presenting the larger context in which this work is integrated, in this case the urgent global water crisis and some of its drivers, means to establish the motivation behind the current work and the significance of this research endeavor.

Literature review – Reviewing the existing literature surrounding the topic of this dissertation is essential to identify research gaps and acquire an overall view of the current scientific efforts being made to address the problem. This work’s review focuses on the textile industry and its water impacts, on the research conducted concerning the raw material hemp and its potential as a textile fiber, and on optimization models developed for sustainable textile supply chains. This step paves the path to deliver meaningful contributions to the targeted scientific field.

Model development – The development of an optimization model for the network design and planning of a supply chain, from a strategic point of view, intends to provide a decision support tool for decision-makers. In this case, the Mixed Integer Linear Programming (MILP) model developed is driven by three objective functions regarding the economic, social and water impact performances of the supply chain.

Data collection – Collecting reliable information to use as input data for the implementation of the case study is a crucial step. It requires thorough research and careful treatment, given that the accuracy of the input data will have a direct impact on the reliability of the model’s results. In this work, various sources were used, and multiple estimations had to be made to obtain the information required for the case study’s construction.

Model validation – Implementing a case study to the model formulated allows to validate it within a real context. To validate the model, a case study concerning an apparel company was designed and implemented. The model was tested under different conditions, for instance, with single and multiple raw materials and final products, and with deterministic and stochastic demand.

Results analysis – Interpreting the results obtained with the implementation of the case study will ultimately allow to draw conclusions regarding the performance of the model. Different analyses were carried out, from an economic, social and water impact perspective. Both single and multiple optimization approaches were taken for these objective functions. The results obtained should allow to give answers to the research questions formulated. It should help finding solutions for the first question, since the model should demonstrate how the supply chain’s network is altered when the water impact takes a stronger stance in the decisions made. To the second question, the model should also deliver the economic, social and water impacts of incorporating a new raw material into the company’s mix.

Recommendations and future research suggestions – The last step focuses on proposing solutions according to the key findings of the analyses. It is vital to acknowledge the study’s limitations, particularly concerning the model’s development, and encourage future research in the field of sustainable and water-conscious supply chains, with special focus in the textile industry.

1.3 Dissertation’s outline

This dissertation is structured in the following six chapters:

- Chapter 1 – Introduction: A brief overview of the problem that motivated this dissertation is made, to provide a contextualization, as well as highlight the relevance of the developed work.
- Chapter 2 – Literature Review: A review of prior conducted research regarding the identified problem is carried out, relevant theoretical concepts are explained and gaps in the current state-of-the-art are identified. The importance of addressing these gaps is underlined.
- Chapter 3 – Methodology: The problem statement and the mathematical model’s specifications are presented.
- Chapter 4 – Case Study: The case study analyzed in this dissertation is described. All the input data used, and its respective retrieval process, are presented and explained. The assumptions made are also addressed.
- Chapter 5 – Results Analysis: The results obtained with the implementation of the case study in the mathematical model are presented and interpreted through a set of in-depth analyses.
- Chapter 6 – Conclusions: The key findings of the study are summarized, and its limitations are addressed. Suggestions for future work are discussed.

2 - Literature Review

This chapter describes the State-of-the-Art concerning the scope of this work. It is sectioned as follows: Section 2.1 addresses the textile industry and its water impact, Section 2.2 reviews the body of literature concerning hemp as a textile raw material, Section 2.3 presents several mathematical models that aim to optimize sustainable supply chain's network design, particularly in the textile industry and, lastly, Section 2.4 presents the current work.

2.1 The textile industry and its impact on water supplies

It is common to address textile supply chains as a "multi-tier supply chain", each tier representing a different level of production. Figure 5 gives an example for this type of segmentation.

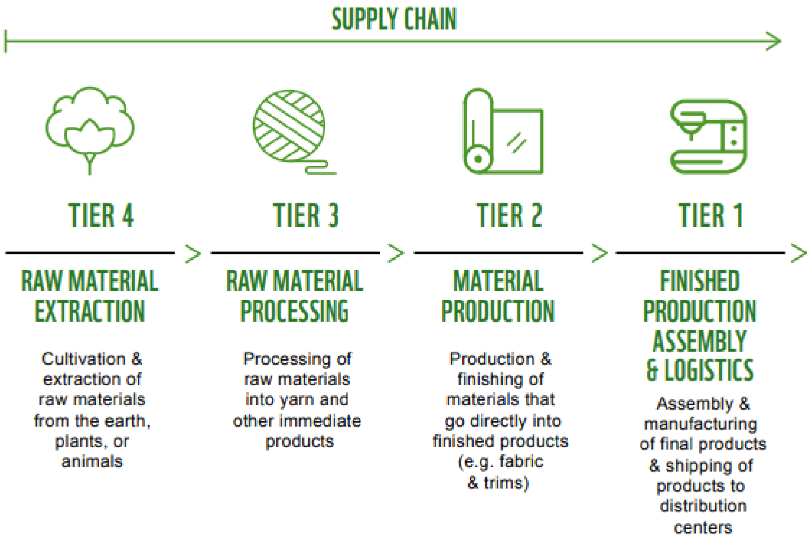

Figure 5: A linear breakdown of the supply chain in the textiles and apparel sector. Adapted from: Morgan, Luthra, et al. (2022).

The whole process starts with the raw material's extraction, assuming the use of natural fibers, either from plants or animals. The next stage, tier 3 in Figure 5, deals with the processing and transformation of fibers into yarn. Tier 2 includes textile manufacturers that produce fabrics, which can either be the final product or a sub-product when considering the production of clothing. This tier can include many processes, such as knitting, weaving and dyeing, depending on the type of fabric characteristics required. Finally, the last tier presented handles final assemblies and other finishing processes.

Recognizing the sector's substantial contribution to global water scarcity and the urgency behind this issue, researchers worldwide have addressed this topic, not only to raise awareness on it, but also to seek solutions that can help reshaping the industry's practices and promote sustainable water management.

As Li et al. (2021) have pointed out, an important step in overcoming this problem is to evaluate how much water is being consumed and how much wastewater is being produced. The authors also highlight the value of employing methods, such as the Water Footprint Assessment (WFA), to obtain these values. The water footprint (WF), concept first introduced by Hoekstra and Hung (2002), measures the total volume of freshwater used, directly and indirectly, in the production of a consumed good or service. On a later study by Chapagain and Hoekstra (2005), the authors develop a framework, by breaking down the concept of water footprint into three types of water use: blue water, correspondent to the withdrawal of ground and surface freshwater for irrigation or processing; green water, which accounts for the evaporation of infiltrated rainwater and, finally, the volume of water required to assimilate and dilute the pollution caused during processing, which would be later designated as grey water by Mekonnen and Hoekstra (2011).

Several of the studies conducted to address the topic of water consumption in the textile industry have employed the WFA while others opted for the Life Cycle Assessment (LCA), a widely accepted methodology to measure the environmental impacts associated with all the life stages of a product or service. Studies by Morgan et al. (2022), Quantis (2018), Chico et al. (2013) and Senthil Kumar et al. (2021), which employed one of these two methods, have all revealed that a significant portion of the water consumption in the textile industry is attributable to the stage of fiber production, which corresponds to tier 4 in Figure 5. As fiber production stands out as an environmental concerning stage in the textile supply chain, it becomes strategically imperative to pursue new practices in this stage of the supply chain. Furthermore, according to Cruz and Tan (2022), in a supply chain characterized by water-dependent raw materials, considering the water footprint indicator is pertinent.

Existing literature has also addressed the importance of following this course of action. Based on an Organizational LCA approach, that aimed to improve the environmental management in the textile industry, Resta et al. (2016) highlight the selection of sustainable material to produce apparel as a possible solution to decrease the sector's environmental impact. This solution is supported by Gedik and Avinc (2020) which state that one of the most important steps in attaining a sustainable production chain for textiles is through the selection of raw material. The authors proceed to bring attention to the hemp fiber, which comprehends significant sustainable production potential for the industry.

2.2 Hemp: a potential water-efficient raw material in textile production

There is an extensive body of literature that highlights hemp (*Cannabis sativa* L.) for its versatility as a crop, justifying a great portion of its growing attractiveness in its multifaceted potential in industrial applications (Amaducci et al., 2015; Andre et al., 2016; Kaur & Kander, 2023). Industrial hemp has also shown significant potential within the textile and apparel sector, as a textile fiber (Gill et al., 2022; Zimniewska, 2022).

In addition to highlighting the appeal of the hemp crop for its multifold applications, Amaducci et al.

(2015) point out the textile industry as one of the oldest documented end use destinations for the plant. The most relevant aspects of hemp cultivation were reviewed by the authors, which concluded that the agronomic factors have a significant impact on determining the yield and quality of hemp fiber production, depending on the specific end uses. It is also expressed that the high resource-use efficiency of the crop can lead to higher yields, thus lower environmental impacts.

Per Andre et al. (2016), one of the reasons why hemp is witnessing a resurgence of interest is due to its agricultural features such as its resistance to drought, pests and soil erosion, as well as its low water requirements comparatively to other crops, namely cotton. This is also proved by Mekonnen and Hoekstra (2011), that found that cotton fibers have a substantially larger water footprint than hemp fibers. According to Gill et al. (2022)**,** there are conflicting studies regarding hemp's water use and drought tolerance. Yet, the authors' analysis ultimately report that hemp is capable of outstanding exceptionally low levels of soil water availability. With drought projected to increase in the future, and considering the water risks that the textile industry's hotspots are exposed to (Morgan, Camargo, et al., 2022), Gill et al. (2022) wrap up by stating that hemp could offer a solution to cropping productivity in water-limited environments.

Zimniewska (2022) builds up on prior research displaying the various benefits of hemp, by performing a review on the current development of hemp fiber processes and textile properties. According to the author, there are other environmental benefits as hemp cultivation allows for the absorption of CO_2, approximately 10 ton per vegetation period, and improves soil quality, aiding in restoring healthy ecosystems. In a detailed description, Zimniewska (2022) presents the possible approaches that can be used for the extraction of the hemp fiber, and the consequent processes needed to achieve the desired fiber properties the final products require. For instance, the decortication process, used for fiber separation, is not a fitting process when the aim is to produce high-quality textiles because the fibers obtained contain a high level of impurities. The author also underlines that the bottleneck of the hemp textile value chain is the spinning system. Due to a lack of specialized equipment, the production of 100% hemp long fiber is still a challenge. Therefore, per the author, the most feasible direction for developing hemp yarn is through the adaptation of cotton spinning systems for cottonized hemp fibers, which allows hemp to be blended with cotton or similar fibers. The cottonized hemp fibers are obtained through a cottonization process that consists in diminishing the impurity level of the fiber, making them thinner, softer and more compatible with cotton (de Queiroz et al., 2020).

Currently, according to Expert Market Research (2023), the global industrial hemp market reached an approximate value of $5 billion and is estimated to grow by 19% annually until 2032. The Asia Pacific is experiencing rapid growth within this sector and the increase in the textile industry's demand is a significant factor propelling the market. Duque Schumacher et al. (2020) focused on examining hemp from an economic standpoint, while still providing interesting environmental results, when comparing hemp to cotton. Some of their insights consisted of hemp requiring less land and water to produce the same amount of fiber as cotton. As for economic considerations, the authors conclude that hemp is economically competitive, thus a feasible sustainable alternative to cotton.

Kaur and Kander (2023) also carried out an extensive review of the current literature on industrial hemp's sustainability from an economic, environmental and social perspective. Per the authors, the hemp supply chain still faces several economic uncertainties and the estimates of the global industrial hemp market size vary significantly and should be approached with caution. The issue pertaining to the lack of specialized machines is also reinforced in their research. It is highlighted that for firms focused on profit maximization, hemp cost must stay competitive with other fibers. Regarding the social dimension, Kaur and Kander (2023) express that hemp's ability to establish local and regional supply chains is linked to its social value as a raw material. Local cultivation of the raw materials should work as an economic incentive to manufacture hemp derived products locally as well, while trading on an international level would give economic value to the regional production. The authors also cover literature that addresses production hazards and workplace safety; however, they conclude by stating that additional research is needed to quantify the social sustainability of industrial hemp.

2.3 Optimization models for sustainable supply chain's network design in the textile industry

Solving problems concerning supply chain design and planning entails an intricate and strategic decision-making approach. Further intensifying the complexity of these decisions is the increasing pressure companies have been under to develop and adopt sustainable business practices, which has significantly amplified corporate interest in Sustainable Supply Chain Management (SSCM) (Hou et al., 2023). This concept refers to implementing all sustainable goals through a triple bottom line approach, which considers the economic, environmental and social dimensions (Ravand and Xu, 2021).

The textile and apparel industry comprises complex supply chains where an efficient network design is a must. Moreover, there is an explicit need for an increase of SSCM-based studies, expressed by Hou et al. (2023) and, particularly, to respond to the growing demand for sustainable supply chains in the textile industry, where companies are, more than ever, attempting to ascertain sustainability practices (Raian et al., 2022).

Mathematical models are a valuable tool for decision-making processes and for network structuring, enabling the achievement of more resilient and efficient supply chain configurations. However, to the best of the author's knowledge, the textile sector has not been the subject of extensive analysis using mathematical programming models. Nonetheless, some researchers have devoted efforts to the study of this industry's supply chains. Paydar et al. (2021), for instance, developed a bi-objective stochastic MILP model for the supply chain design of the clothing industry, where the optimization of total profit and downside risk drove the decisions made by the model.

In Table 1, an effort was made to provide other relevant examples of studies that, not only employed mathematical programming models to strategically optimize supply chain network design in the textile industry, but also assumed a broader stance and incorporated other aspects beyond just economic considerations. The main key words that led to the following research papers presented were “textile industry”, “optimization”, “supply chain” and “sustainability”.

Table 1: Examples of research papers that use mathematical optimization in integrated textile supply chain models.

Research Paper Reference	**Model**	**Economic Considerations**			**Environmental Considerations**			**Social Impact**	**Objective Functions**	**Uncertainty**
		Costs	**Profit**	**NPV**	**CO_2**	**Water**	**Other**			
Mezatio et al. (2022)	MILP	✓			✓				Costs minimization	Multiple scenarios of carbon price and demands
Shaw et al. (2013)	GP	✓			✓				Costs minimization Direct CO_2 emission minimization Indirect CO_2 emission minimization Trade-credit maximization	-
Moreno-Camacho et al. (2020)	MILP	✓			✓			✓	Costs minimization CO_2 emission minimization Employment maximization	-
Jafari et al. (2017)	MOVDO	✓				✓		✓	Costs minimization Groundwater consumption minimization Employment maximization	-
Current Work	**MILP**			✓	✓	✓	✓	✓	**NPV maximization** **Water impact minimization** **Employment maximization**	**Stochastic demand**

The first study displayed in Table 1, conducted by Mezatio et al. (2022), successfully integrates carbon emission in a textile supply chain management planning, considering both economic and environmental issues. It relies on a MILP approach to solve the model developed, which optimizes total costs. The case study analyzed deals with different carbon prices and demands and the results obtained indicate that carbon price uncertainty can have a significant impact on the economic and environmental supply chain management.

Granting the remaining three research papers presented do not address uncertainty within the supply chain, they still offer an important contribution to the textile supply chain network design literature. Shaw et al. (2013) proposed a sustainable supply chain design that aimed to optimize total cost, direct carbon emissions, indirect carbon emissions, in the form of embodied carbon footprint, and total trade-credit amount over purchasing cost. The authors solved the model through a multi-objective Goal Programming (GP). Despite its comprehensive take on carbon emissions, there is no consideration for any other environmental aspects nor for the social dimension of sustainability.

Moreno-Camacho et al. (2020) developed a multi-objective MILP model to optimize the design of a sustainable textile supply chain. The authors take into account all three dimensions of sustainability by minimizing costs (economic), minimizing the level of carbon emissions (environmental) and maximizing the number of jobs opportunities created, while considering the social behavior of the suppliers selected through categories such as labor equity and healthcare, among others.

The conducted literature review unveiled a notable oversight on water-related supply chain impacts within optimization models applied in textile supply chain’s network designs. That being said, a few studies do address this environmental issue. It is the case of the last research paper presented in Table 1, conducted by Jafari et al. (2017) that offer a broad contribution to the study of sustainable closed-loop supply chain networks. The researchers employ a Multi-Objective Vibration Damping Optimization (MOVDO), Pareto based algorithm to solve the proposed model which optimizes total costs, minimizes the negative effects of wasteful extraction of groundwaters and the pollution resulting from industrial wastewaters and, lastly, maximizes employment. Although it does not deliver exact solutions, the results of the study display its contribution for supply chains facing the water crisis. The authors also focus on water recycling as a consuming byproduct material in production processes.

2.4 Current work

The present work successfully integrates the triple bottom line of sustainability in a multi-objective optimization MILP model, each objective function representative of one of the three pillars.

Besides the economic performance, the model developed addresses water, and its impact in the supply chain, as an optimization objective, proposing a broad approach to assess water impact. It involves employing the water footprint for the raw materials used in the supply chain, as already done by other practitioners (Cruz & Tan, 2023; Rajakal et al., 2021), albeit not specifically directed towards the textile sector. In addition, it considers the water stress level index of the various regions where the supply chain’s entities can be located, an approach that, to the best of the author’s knowledge, has not been done so far. It also factors in the water consumed on the different activities taking place within the supply chain, which has also been accomplished in previous studies (Abdali et al., 2021). Considering the water footprint of raw materials is especially important given that the current work studies the impacts of the introduction of hemp as a textile raw material as encouraged by many researchers (Gill et al., 2022; Duque Schumacher et al., 2020).

Not unlike Kaur and Kander (2023), considerations for the economic, environmental and social impacts will be drawn. It should be noted that, despite also addressing other environmental impacts of the supply chain, this work’s environmental considerations are primarily focused on water impacts. The model developed in this work also includes the social dimension as an objective function, which measures the employment generated in the supply chain, as already done by Moreno-Camacho et al. (2020) and Jafari et al. (2017). Finally, a stochastic approach is also adopted, to analyze different demand forecasts.

This study intends to contribute to the body of research of SSCM-based models and studies, particularly in the textile and apparel industry, where there is still a shortage of models for supply chain network design and planning, that optimize the economic, environmental and social dimensions.

3 - Methodology

This chapter is dedicated to defining the problem that will be covered in this work. Section 3.1 presents the problem statement, in which the general outlines of the problem are drawn. Section 3.2 details the developed mathematical formulation of the previously described problem and Section 3.3 presents the approach used for the multi-objective optimization.

3.1 Problem statement

This work aims to contribute to the research concerning sustainable water management strategies in supply chains, which has been a growing necessity due to the worsening global water crisis. It does so by focusing on a highly globalized and water dependent industry, the textile industry, which has Asia as its production and exports epicenter.

In a world where the water crisis is already a serious issue to face, this concern can only be expected to grow with the forecasted expansion of population’s consumption, particularly, of the global middle class. The expected increase in pressure that a larger population will put in the scarcely available water resources is a major problematic by itself. Moreover, when factoring in the rise of the middle class and the continuous thriving of fast fashion.

From the water consumed in the agricultural stage, where the cotton crop continues to hold a dominant position, to the water consumption of textile fabrication, dyeing and finishing; the sector is one of the largest freshwater users in the world. Furthermore, apparel production is globally distributed in clusters, many of which concentrated in smaller regions close to large river deltas, where the natural resources have long endured excessive exploitation and pollution. This led to an increase of water scarcity in those areas. The creation of these clusters was also highly influenced by the low labor costs practiced in the countries they include, given that the garment sector profits tremendously by outsourcing production activities to low and middle-income countries.

Although some research has been conducted regarding the textile industry and its water intensive processes, it is still of the utmost importance to continue to study alternative ways to reduce the sector’s water impact. The adoption of other fibers as raw materials, less water dependent than cotton, has also been a subject of ongoing investigation. In this research, however, there is a lack of generic supply chain models that not only address the three sustainability pillars, but also focus on the supply chain’s water impact. These models can be an extremely valuable tool to study the impact of different water management strategies in supply chains.

This gap is addressed in the current work, as it offers a decision support tool for the network design and planning of a supply chain, from a strategic perspective. In this framework, the economic, social and environmental pillars are taken under consideration, with particular focus on water impact on the environmental dimension. A generic mathematical MILP model was developed and later applied to a case study of an apparel company, in order to validate the framework and provide insights into the impact a company of this sector can have. This model was developed from the ground-up and it considers a supply chain as depicted in Figure 6. The model's structure incorporates elements from existing models, with a special emphasis on the model developed by Mota et al. (2018), which deals with the design and planning of closed loop sustainable supply chains. Particularly, the authors take on the economic objective function, considering the maximization of the Net Present Value and on the social objective function, which involves maximizing the number of jobs created in the supply chain, provided reference points for the economic and social objective functions delineated in this dissertation. Additionally, the environmental objective function developed by Mota et al. (2018) laid the formulation groundwork for the environmental assessment conducted in the current work.

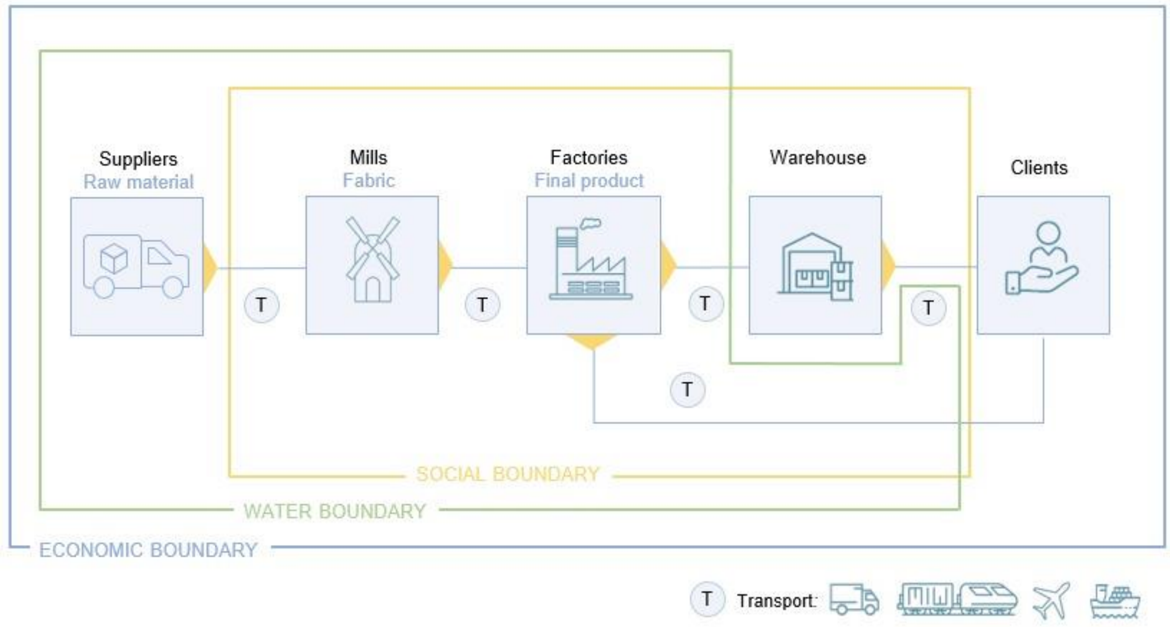

Figure 6: Supply chain representation.

Figure 6 translates the following chain of events. Raw materials flow from suppliers to mills, where they are transformed into fabric, in a first stage of production. Afterwards, the fabric flow is directed to the factories for the second, and last, stage of production, where the fabric is transformed into final product. The final products can then flow directly to the clients or be stored in warehouses, as inventory. Inventory is only allowed in warehouses, and in the form of final product. Transportation between entities can be done by unimodal or intermodal transport, which includes road, rail, air and sea transport. To perform intermodal transport, the flow must first be directed to an airport, seaport or railway station by truck where it will be able to be transported by plane, boat or train, respectively.

Each of the three objective functions represent one of the three sustainability pillars, considering that the environmental objective function focuses on the water impact of the supply chain. Figure 6 also presents the boundaries considered for each of the objective functions. The economic objective function focuses on the maximization of the Net Present Value, the water objective function minimizes the total water impact of the supply chain, and the social goal aims to maximize the generation of employment within the supply chain. Although not modelled as an objective function, the overall environmental impact, that is, considering impact categories other than the water use, is also assessed, for the agriculture and raw material processing, production and transportation activities. The model's output will offer valuable insights regarding the optimization of an apparel supply chain by shedding light on the economic, water and social impacts it causes.

Overall, given:

- Available locations of entities;
- Available capacities of suppliers, mills, factories and warehouses;
- Initial inventory levels of final product;
- Number of necessary employees, per ton of product, in mills, factories, warehouses;
- Number of necessary employees, per ton of transported product in truck, train, plane and boat;
- Raw material costs, per ton of product;
- Production costs, per ton of produced product;
- Inventory costs, per ton of product;
- Hub costs, per country;
- Lease costs, per country;
- Transportation costs, per transport mode and ton of product;
- Labor costs, per country;
- Final product price, per country;
- Bill of materials (BOM);
- Annual demand;
- Distances between entities (km);
- Water stress level, per country;
- Amount of used water in raw material's cultivation and treatment (water footprint), per ton of product;
- Amount of consumed water in production, per ton of produced product;
- Amount of consumed water in transportation, per ton of product and per km.

The goal is to obtain:

- The network structure.
- The transportation's network.
- The quantity of supply flow by each supplier in the network, per type of raw material.
- The production level in each mill in the network, per type of fabric.
- The production level in each factory in the network, per type of final product.
- The storage levels, per type of final product.

So as to:

- Maximize Net Present Value.
- Minimize Water Impact (considering raw materials' water footprint, operations' water consumption and network locations' water stress).
- Maximize the social indicator of annual number of jobs created by the supply chain, per year.

3.2 Mathematical formulation

The current section aims to present the developed mathematical model's formulation.

3.2.1 Indices and related sets

i, j ϵ I: Locations of entities $I = I_{sup} \cup I_m \cup I_f \cup I_w \cup I_c \cup I_{air} \cup I_{sea} \cup I_{rail}$

I_{sup}: Suppliers

I_m: Mills

I_f: Factories

I_w: Warehouses

I_c: Clients

I_{air}: Airports

I_{sea}: Seaports

I_{rail}: Railway stations

p, q ϵ P: Products $P = P_{rm} \cup P_{fab} \cup P_{fp}$

P_{rm}: Raw material

P_{fab}: Fabric

P_{fp}: Final product

t ϵ T: Transport modes $T = T_{pla} \cup T_{boa} \cup T_{tra} \cup T_{tru}$

T_{pla}: Plane

T_{boa}: Boat

T_{tra}: Train

T_{tru}: Truck

k ϵ K: Time periods $K = K_{first} \cup K_{other}$

K_{first}: First time period

K_{other}: All but first time period

c ϵ C: Environmental midpoint categories

U: Allowed entity-entity connections $U = \{(i, j): i, j \in I\}$

For the description of this subset, please consider the following:

U_{supm} : Connection between supplier and mill

U_{mf} : Connection between mill and factory

U_{fc} : Connection between factory and client

U_{fw} : Connection between factory and warehouse

U_{wc} : Connection between warehouse and client

As for airports, seaports and railways, all connections are possible.

For transportation restrictions purposes, the following were also computed:

U_{land} : Connection between non-island countries

$U_{islands}$: Connection between island countries

$U_{land\_islands}$: Connection between non-island and island countries

$U_{islands\_land}$: Connection between island and non-island countries

V: Allowed product-entity relations $V = \{(p,i): p \in P \wedge i \in I\}$

For the description of this subset, please consider the following:

V_{suprm} : Relation between supplier and raw material

V_{mrm} : Relation between mill and raw material

V_{mfab} : Relation between mill and fabric

V_{ffab} : Relation between factory and fabric

V_{ffp} : Relation between factory and final product

V_{wfp} : Relation between warehouse and final product

V_{cfp} : Relation between client and final product

As for airports, seaports and railways, all relations are possible.

F: Allowed flows of materials between entities $F = \{(p,i,j): (p,i) \in V \wedge (i,j) \in U\}$

For the description of this subset, please consider the following examples:

$F_{OUTsuprm}$: Flow out (OUT) of raw material (RM) that leaves suppliers (SUP) and enters entity j

F_{INmrm} : Flow in (IN) of raw material (RM) that leaves an entity i and enters the mills (M)

Net: Allowed transport modes in connections between entities $Net = \{(t,i,j): t \in T \wedge (i,j) \in U\}$

Net_{plane} : Connections between airports by plane

Net_{boat} : Connections between seaports by boat

Net_{train} : Connections between railway stations by train

Net_{truck} : All remaining connections

NetCon: Network with all allowed connections $NetCon = \{(t, p, i, j): (t, i, j) \in Net \wedge (p, i, j) \epsilon\ F\}$

3.2.2 Parameters

Entity related parameters:

$scap_{pi}$: Maximum supply capacity for raw material p by supplier i (ton)

$mcap_i$: Maximum production capacity in mill i (ton)

$fcap_i$: Maximum production capacity in factory i (ton)

$wcap_i$: Maximum inventory capacity in warehouse i (ton)

ii_{pi} : Inventory level of product p in warehouse i in time period 1 (ton)

w_i : Necessary number of workers in entity i to produce/store one ton of product

p_i : Price per unit sold in client i (c.u.)

d_{ik} : Demand by client i in time period k (ton)

ws_i : Water stress level index for each entity i

wcf : Water consumption of fabric production (m^3/ton)

$wcfp$: Water consumption of final product production (m^3/ton)

Product related parameters:

BOM_{pq}^{fab}: First stage production bill of materials that specifies the amount of raw material p necessary to produce one ton of fabric q

BOM_{pq}^{fp}: Last stage production bill of materials that specifies the amount of fabric p necessary to produce one ton of final product q

BOM_{pq}^{m}: Bill of materials at mills

BOM_{pq}^{fw}: Bill of materials at factories and warehouses

BOM_{pq}^{t}: Bill of materials at airports, seaports and railway stations

wf_{pi} : Water footprint of each raw material p in each location of supplier i

fpw : Final product's weight (ton)

Transport and Environment related parameters:

wct_t : Water consumption of each transport mode t (per tkm)

w_t : Average number of jobs created per transport mode t in airports, seaports and railway station (per tkm)

ei_{pc}^{rm}: Environmental impact characterization factor of raw material p processing, at midpoint category c (per ton)

ei_{pc}^{fab}: Environmental impact characterization factor of fabric p production, at midpoint category c (per ton)

ei_{pc}^{fp}: Environmental impact characterization factor of final product p production, at midpoint category c (per ton)

ei_{tc}: Environmental impact characterization factor of transport mode t, at midpoint category c (per tkm)

n_c: Normalization factor for midpoint category c

Costs:

rmc_{pi}: Cost of raw material p supplied by supplier i (c.u./ton)

pmc: Production cost at mills (c.u./ton)

pfc: Production cost at factories (c.u./ton)

ic: Inventory cost at warehouses (c.u./ton)

hc_i: Hub cost of entity i (c.u.)

tc_{it}: Transport cost for each transport mode t from location i, per tkm (c.u.)

$labc_i$: Labor cost of entity i (c.u.)

lc_i: Lease cost of entity i (c.u.)

Others:

$dist_{ij}$: Distance between entity i and entity j (km)

$BigM$: Large number

$SmallM$: Small number

ny: Time horizon (years)

tr: Tax rate

ir: Interest rate

3.2.3 Decision variables

Continuous and positive variables:

X_{pijtk}: Amount of product p transported by transport mode t from entity i to entity j in time period k

S_{pik}: Amount of inventory of final product p in warehouse i in time period k

W_{pik}: Amount of product p produced in entity i in time period k

Binary variable:

Y_i = 1 if entity i is used (excludes suppliers), 0 otherwise

3.2.4 Constraints

Material balances

Material balance at mills:

Constraints (1) and (2) model the material balance at mills. Constraint (1) assures that the production of fabric at mills (first term), during all time periods, is equal to the outgoing flow of fabric (second term). Constraint (2) sets the necessary amount of raw material to be sent by the supplier, by matching the amount of ingoing flow of raw material (first term) with the level of production of fabric (second term). These constraints assure that there is no possibility of stock in mills, as all the flow of material that enters the mills is used for the production in that same time period.

$$W_{pik} = \sum_{\substack{t:(t,q,i,j)\,\in\, NetCon \\ (q,j):(q,i,j)\,\in\, F_{OUTmfab}}} BOM_{pq}^{m} \cdot X_{qijtk}\,, \quad p \in P_{fab} \;\; i \in I_m \;\wedge k \in K \tag{1}$$

$$\sum_{\substack{t:(t,p,i,j)\,\in\, NetCon \\ i:(p,i,j)\,\in\, F_{INmrm}}} X_{pijtk} = \sum_{q\,\in\, P_{fab}} W_{qjk} \cdot BOM_{pq}^{fab}, \quad j \in I_m \;\wedge p \in P_{rm} \wedge k \in K \tag{2}$$

Material balance at factories:

Constraints (3) and (4) model the material balance at factories. Constraint (3) expresses that the production of final product at the factories (first term), for all time periods, equals the outgoing flow from the factories (second term). Constraint (4) models the production of final product and, by matching the amount of ingoing flow of fabric (first term) with the production level of final product at the factory (second term). These constraints combined ensure, not unlike the mills, that there is no possibility for stock at the factories.

$$W_{pik} = \sum_{\substack{t:(t,q,i,j)\,\in\, NetCon \\ (q,j):(q,i,j)\,\in\, F_{OUTffp}}} BOM_{pq}^{fw} \cdot X_{qijtk}\,, \quad p \in P_{fp} \; i \in I_f \;\wedge k \in K \tag{3}$$

$$\sum_{\substack{t:(t,p,i,j)\,\in\, NetCon \\ i:(p,i,j)\,\in\, F_{INffab}}} X_{pijtk} = \sum_{q\,\in\, P_{fp}} W_{qjk} \cdot BOM_{pq}^{fp}, \quad j \in I_f \;\wedge p \in P_{fab} \wedge k \in K \tag{4}$$

Material balance at warehouses in time period 1:

The material balance at warehouses is implemented with constraints (5) and (6). Constraint (5) states that the initial stock of final product and its inbound flow to the warehouse (first term) is equal to the amount kept in stock plus the outgoing flow of final product (second term), during the first time period.

$$ii_{pi} + \sum_{\substack{t:(t,q,i,j) \in NetCon \\ (q,j):(q,i,j) \in F_{INwfp}}} BOM_{pq}^{fw} \cdot X_{qijtk} = S_{pik} + \sum_{\substack{t:(t,q,i,j) \in NetCon \\ (q,j):(q,i,j) \in F_{OUTwfp}}} BOM_{pq}^{fw} \cdot X_{qijtk}, \tag{5}$$

$$i \in I_W \wedge p \in P_{fp} \wedge k \in K_{first}$$

Material balance at warehouses in remaining time periods:

Constraint (6) models the remaining time periods by simply replacing the initial stock of final product ii_{pi} with the remaining stock from the previous time period $S_{pi(k-1)}$.

$$S_{pi(k-1)} + \sum_{\substack{t:(t,q,i,j) \in NetCon \\ (q,j):(q,i,j) \in F_{INwfp}}} BOM_{pq}^{fw} \cdot X_{qijtk} = S_{pik} + \sum_{\substack{t:(t,q,i,j) \in NetCon \\ (q,j):(q,i,j) \in F_{OUTwfp}}} BOM_{pq}^{fw} \cdot X_{qijtk}, \tag{6}$$

$$i \in I_W \wedge p \in P_{fp} \wedge k \in K_{other}$$

Cross-docking at airports, seaports and railway stations:

Constraints (7), (8) and (9) state that the inbound flow at an airport, seaport and railway station, respectively, equal their outbound flow, ensuring that the airports, seaports and railway stations only operate as cross-docking points.

$$\sum_{\substack{t:(t,q,i,j) \in NetCon \\ (q,j):(q,i,j) \in (F_{INairrm} \\ \cup F_{INairfab} \\ \cup F_{INairfp})}} BOM_{pq}^{t} \cdot X_{qijtk} = \sum_{\substack{t:(t,q,i,j) \in NetCon \\ (q,j):(q,i,j) \in (F_{OUTairrm} \\ \cup F_{OUTairfab} \\ \cup F_{OUTairfp})}} BOM_{pq}^{t} \cdot X_{qijtk}, \tag{7}$$

$$(p,i) \in (V_{airrm} \cup V_{airfab} \cup V_{airfp}) \wedge k \in K$$

$$\sum_{\substack{t:(t,q,i,j) \in NetCon \\ (q,j):(q,i,j) \in (F_{INsearm} \\ \cup F_{INseafab} \\ \cup F_{INseafp})}} BOM_{pq}^{t} \cdot X_{qijtk} = \sum_{\substack{t:(t,q,i,j) \in NetCon \\ (q,j):(q,i,j) \in (F_{OUTsearm} \\ \cup F_{OUTseafab} \\ \cup F_{OUTseafp})}} BOM_{pq}^{t} \cdot X_{qijtk}, \tag{8}$$

$$(p,i) \in (V_{searm} \cup V_{seafab} \cup V_{seafp}) \wedge k \in K$$

$$\sum_{\substack{t:(t,q,i,j)\,\in\,NetCon \\ (q,j):(q,i,j)\,\in\,(F_{INrailrm} \\ \cup\, F_{INrailfab} \\ \cup\, F_{INrailfp})}} BOM_{pq}^{t} \cdot X_{qijtk} = \sum_{\substack{t:(t,q,i,j)\,\in\,NetCon \\ (q,j):(q,i,j)\,\in\,(F_{OUTrailrm} \\ \cup\, F_{OUTrailfab} \\ \cup\, F_{OUTrailfp})}} BOM_{pq}^{t} \cdot X_{qijtk}, \tag{9}$$

$$(p,i) \in (V_{railrm} \cup V_{railfab} \cup V_{railfp}) \wedge k \in K$$

Entity capacity constraints

Entity existence constraints:

Constraints (10) and (11) were created to define the decision variable Y_i. These state that, within the network, an entity is only used in the network (Y_i = 1) if there is an ingoing flow to that same entity. These constraints exclude the suppliers, as they only have an outgoing flow.

$$\sum_{(t,p,j):(t,p,i,j)\,\in\,NetCon} X_{pijtk} \leq BigM \cdot Y_i, \;\; i \in I \backslash I_{sup} \;\wedge k \in K \tag{10}$$

$$\sum_{(t,p,j):(t,p,i,j)\,\in\,NetCon} X_{pijtk} \geq SmallM \cdot Y_i, \;\; i \in I \backslash I_{sup} \;\wedge k \in K \tag{11}$$

Supply capacity:

The maximum supply capacity is modelled through constraint (12).

$$\sum_{\substack{(t,j):(t,p,i,j)\,\in\,NetCon \\ j:(p,i,j)\,\in\,F_{OUTsuprm}}} X_{pijtk} \leq scap_{pi}, \;\; i \in I_{sup} \;\wedge p \in P_{rm} \wedge k \in K \tag{12}$$

Production capacities:

Constraints (13) and (14) implement the maximum and minimum production capacity limits at mills, respectively. The same is done for factories through constraints (15), for the maximum, and (16) for the minimum production capacity. Both in mills and factories, the production level must reach at least 50% of the total production capacity of that entity, for it to integrate the network. A minimum capacity, besides ensuring that the mills and factories are not being used at an undesired low capacity, also guarantees that the production levels, driven by the demand, are more evenly distributed in the mills and factories used.

$$\sum_{p\,\in\,P_{fab}} W_{pik} \leq mcap_i \cdot Y_i\,, \;\; i \in I_m \;\wedge k \in K \tag{13}$$

$$\sum_{p\,\in\,P_{fab}} W_{pik} \geq 0.5 \cdot mcap_i \cdot Y_i\,, \;\; i \in I_m \;\wedge k \in K \tag{14}$$

$$\sum_{p \in P_{fp}} W_{pik} \leq \ fcap_i \cdot Y_i \,, \ \ i \in I_f \ \wedge k \in K \tag{15}$$

$$\sum_{p \in P_{fp}} W_{pik} \geq \ 0.5 \cdot fcap_i \cdot Y_i \,, \ \ i \in I_f \ \wedge k \in K \tag{16}$$

Inventory capacity:

Constraint (17) sets the maximum inventory capacity for warehouses.

$$\sum_{p \in P_{fp}} S_{pik} \leq \ wcap_i \cdot Y_i \,, \ \ i \in I_w \ \wedge k \in K \tag{17}$$

Transportation constraints

The following constraints ensure that the flow of material going into an airport (18), seaport (19) and railway station (20) are transported to another airport, seaport and railway station, respectively. Furthermore, they ensure that the transportation is made through a plane, for constraint (18), a boat for constraint (19) and a train for constraint (20).

$$\sum_{\substack{(t,j):(t,p,i,j) \in NetCon \\ j \in I \setminus (I_{air})}} X_{pijtk} = \sum_{\substack{(t,j):(t,p,i,j) \in NetCon \\ j \in I_{air}}} X_{pijtk}, \tag{18}$$

$$(p,i) \in (V_{airrm} \cup V_{airfab} \cup V_{airfp}) \ \wedge \ k \in K$$

$$\sum_{\substack{(t,j):(t,p,i,j) \in NetCon \\ j \in I \setminus (I_{air})}} X_{pijtk} = \sum_{\substack{(t,j):(t,p,i,j) \in NetCon \\ j \in I_{air}}} X_{pijtk}, \tag{19}$$

$$(p,i) \in (V_{airrm} \cup V_{airfab} \cup V_{airfp}) \ \wedge \ k \in K$$

$$\sum_{\substack{(t,j):(t,p,i,j) \in NetCon \\ j \in I \setminus (I_{rail})}} X_{pijtk} = \sum_{\substack{(t,j):(t,p,i,j) \in NetCon \\ j \in I_{rail}}} X_{pijtk}, \tag{20}$$

$$(p,i) \in (V_{railrm} \cup V_{railfab} \cup V_{railfp}) \ \wedge \ k \in K$$

Demand constraint

The demand is modelled through constraint (21). Since the demand by each client must be satisfied, this constraint operates as a driver for all the network's flows.

$$\sum_{\substack{t:(t,p,i,j) \in NetCon \\ (p,i):(p,i,j) \in F_{INcfp}}} X_{pijtk} = \ d_{ik}, \ \ j \in I_c \ \wedge k \in K \tag{21}$$

3.2.5 Objective functions

Economic

To obtain the economic objective function, measured through the NPV, it was first necessary to model equations to represent the costs and ensuing cash-flow of the network.

The raw material costs are given by equation (22).

$$RawMaterialCost_k = \sum_{\substack{t:(t,p,i,j) \in NetCon \\ (p,i,j):(p,i,j) \in F_{OUTsuprm}}} X_{pijtk} \cdot rmc_{pi}, \;\; k \in K \tag{22}$$

The production costs are expressed in equation (23).

$$ProductionCost_k = \sum_{(p,i):(p,i) \in V_{mfab}} W_{pik} \cdot \; pmc + \sum_{(p,i):(p,i) \in V_{ffp}} W_{pik} \cdot \; pfc \,, \;\; k \in K \tag{23}$$

The stock costs are modelled through expression (24).

$$StockCost_k = \sum_{(p,i):(p,i) \in V_{wfp}} S_{pik} \cdot ic, \quad k \in K \tag{24}$$

The hub costs are given by equation (25).

$$HubCost_k = \sum_{i:\; I_{air} \cup I_{sea} \cup I_{rail}} hc_i \cdot Y_i, \quad k \in K \tag{25}$$

The transport costs are translated in expression (26).

$$TransportCost_k = \sum_{(t,p,i,j):(t,p,i,j) \in NetCon} X_{pijtk} \cdot tc_{it} \cdot dist_{ij}, \quad k \in K \tag{26}$$

The labor costs are given by expression (27).

$$LaborCost_k = \sum_{(p,i):(p,i) \in (V_{mfab} \cup V_{ffp})} W_{pik} \cdot labc_i \cdot w_i \; + \sum_{(p,i):(p,i) \in V_{wfp}} S_{pik} \cdot \; labc_i \cdot w_i, \tag{27}$$

$$k \in K$$

The lease costs are expressed in equation (28).

$$LeaseCost_k = \sum_{i:\ I_m \cup I_f \cup I_w} lc_i \cdot Y_i, \quad k \in K \tag{28}$$

The cash-flow per time period was computed through equation (29).

It comprises the difference between the revenue obtained by the company for every unit of product sold and the total costs incurred by the company, accounting for the tax rate discount.

$$CashFlow_k = (1 - tr) \cdot (\sum_{\substack{t:(t,p,i,j) \in NetCon \\ (p,i,j):(p,i,j) \in F_{INcfp}}} (p_i \cdot \frac{X_{pijtk}}{fpw}) - RawMaterialCost_k - ProductionCost_k - StockCost_k - HubCost_k - TransportCost_k - LaborCost_k - LeaseCost_k), \; k \in K \tag{29}$$

The economic objective function is translated in equation (30). It was defined to maximize the NPV, which corresponds to the sum of each time period's cash-flow, while factoring in the interest rate. Seeing as there were no investments under consideration, there was no need to factor in depreciations.

$$\max NPV = \sum_{k \in K} \frac{CashFlow_k}{(1 + ir)^k} \tag{30}$$

Water Impact

The water impact objective function was formulated to minimize the water impact of different stages of the supply chain. This water impact encompasses the water consumed in the processes occurring in these stages and the water stress level of the region in which they take place. To achieve this, the following four expressions were computed. Equation (31) represents the water impact of the raw material cultivation and treatment, equation (32) considers the water impact of the first level of production (fabric production) and equation (33) of the last level of production (final product production).

$$WaterImpact\_RM_{pk} = \sum_{\substack{t:(t,p,i,j) \in NetCon \\ (i,j):(p,i,j) \in F_{OUTsuprm}}} X_{pijtk} \cdot wf_{pi} \cdot ws_i, \; p \in P_{rm} \wedge k \in K \tag{31}$$

$$WaterImpact\_FAB_{pk} = \sum_{i \in I_m} W_{pik} \cdot wcf \cdot ws_i, \; p \in P_{fab} \wedge k \in K \tag{32}$$

$$WaterImpact\_FP_{pk} = \sum_{i \in I_f} W_{pik} \cdot wcfp \cdot ws_i, \; p \in P_{fp} \wedge k \in K \tag{33}$$

The water consumption related to the transport operations of the network was modelled through expression (34).

$$WaterImpact\_Trans_{tk} = \sum_{(p,i,j)\,\in\, NetCon(t,p,i,j)} X_{pijtk} \cdot dist_{ij} \cdot wct_t \cdot ws_i,\ \ t \in T \wedge k \in K \tag{34}$$

The water impact objective function is expressed in equation (35). It states that to minimize the supply chain’s water impact, the added water impacts of the four main activities considered of the supply chain must be minimized.

$$\begin{gathered}\min WaterImpact = \textstyle\sum_{k\,\in\, K} \sum_{P\,\in\, P_{rm}} WaterImpact\_RM_{pk} + \\ \textstyle\sum_{k\,\in\, K} \sum_{P\,\in\, P_{fab}} WaterImpact\_FAB_{pk} + \sum_{k\,\in\, K} \sum_{P\,\in\, P_{fp}} WaterImpact\_FP_{pk} + \\ \textstyle\sum_{k\,\in\, K} \sum_{t\,\in\, T} WaterImpact\_Trans_{tk}\end{gathered} \tag{35}$$

Social

The social performance of the supply chain was measured through the number of jobs created by the supply chain per year, which aims to be maximized. Therefore, the following equation (36) represents the social objective function, which accounts for the jobs created in the production and storage operations, as well as in the transportation activities.

$$\begin{gathered}\max JobCreation = \sum_{\substack{(p,i,k):(p,i)\,\in\,(V_{mfab}\,\cup\, V_{ffp})\\ k\,\in\, K}} \frac{W_{pik}\cdot w_i}{ny} + \sum_{\substack{(p,i,k):(p,i)\,\in\,(V_{wfp})\\ k\,\in\, K}} \frac{S_{pik}\cdot w_i}{ny} + \\ \sum_{\substack{(t,p,i,j,k):(p,i,j)\,\in\, NetCon\\ k\,\in\, K\\ t\,\in\, T}} \frac{X_{pijtk}\cdot w_t\cdot dist_{ij}}{ny}\end{gathered} \tag{36}$$

Environmental

Although not modelled as an objective function in the current work, the importance of addressing the environmental impact becomes apparent when exploring more sustainable supply chains. For this reason, a set of equations were modelled in order to account for the environmental dimension while considering other environmental impact categories, and not just water use.

The environmental impact related to the raw material is accounted for with expression (37), while equations (38) and (39) express the environmental impact of the production and transportation activities, respectively.

$$EnvImpact\_RM_{pc} = \sum_{\substack{t:(t,p,i,j)\,\in\, NetCon\\ (i,j):(p,i,j)\,\in\, F_{OUTsuprm}}} X_{pijtk} \cdot ei_{pc}^{rm} \cdot n_c,\ \ p \in P_{rm} \wedge c \in C \tag{37}$$

$$EnvImpactProduction_{pc} \quad = \sum_{i \in I_m} W_{pik} \cdot ei_{pc}^{fab} \cdot n_c + \sum_{i \in I_f} W_{pik} \cdot ei_{pc}^{fp} \cdot n_c, \tag{38}$$

$$p \in (P_{fab} \cup \; P_{fab}) \wedge c \in C$$

$$EnvImpact\_Trans_{tc} = \sum_{(p,i,j) \in NetCon(t,p,i,j)} X_{pijtk} \cdot dist_{ij} \cdot ei_{tc} \cdot n_c, \;\; t \in T \wedge c \in C \tag{39}$$

Equation (40) provides the full environmental impact of the supply chain per midpoint category. These categories will be further discussed in the following chapter. Note that, to model the environmental impact as an objective function, it would only be necessary to add an equation that would comprise the sum of every midpoint category's environmental impact, and then model it to be minimized.

$$EnvImpact\_Category_c = \textstyle\sum_{p \in P_{rm}} EnvImpact\_RM_{pc} + \\ \textstyle\sum_{p \in (P_{fab} \cup P_{fp})} EnvImpact\_Production_{pc} + \sum_{t \in T} EnvImpact\_Trans_{tc} \;, \;\; c \in C \tag{40}$$

3.3 Multi-objective optimization approach

In a multi-objective mathematical programming problem, such as the one implemented in this work, there is not one single optimal solution. For these problems, the aim is not to reach one optimal solution but to find the set of feasible solutions that cannot be improved in one objective function without compromising the result of one, or more, of the remaining. This set of solutions is commonly known as the Pareto Front (Mavrotas, 2009).

According to Mavrotas (2009), there are several approaches that can be taken to face multi-objective problems, such as the priori, interactive and posteriori methods. These designations are suggestive of the moment in the process where the decision-makers pass their judgement. Per the author, the posteriori approach allows for a more informed decision as the decision-maker can formulate its verdict based on the Pareto Front obtained.

In this work, a lexicographic optimization and ε-constraint method were employed, the last a posteriori approach. The ε-constraint is a well-regarded method for efficiently addressing multiple-objectives problems (Huy et al. 2023). The lexicographic technique is first used to define the payoff table and then the ε-constraint delivers the Pareto solutions through the Pareto Front.

4 - Case Study

The current chapter will introduce the case study in which the mathematical model previously described was implemented to be validated. Section 4.1 describes the currently available network for the company featured in the case study, as well as the input data collection and treatment. Section 4.2 covers the different scenarios explored in the case study, to provide a more in-depth understanding of how the model performs for different demand forecasts.

4.1 Problem description and input data

The developed model was implemented in the following case study regarding the supply chain of an apparel company with a market based in Asia. More precisely, the supply chain of a particular item of clothing – jeans. Currently the company only sells one family of final products, made 100% of cotton. However, in light of the worsening water crisis, different strategies and practices to lessen its water impact are to be explored, for instance, with the introduction of a new type of final product, partially made of less water-intensive raw materials, such as hemp. The case study's specific representation is described in Figure 7.

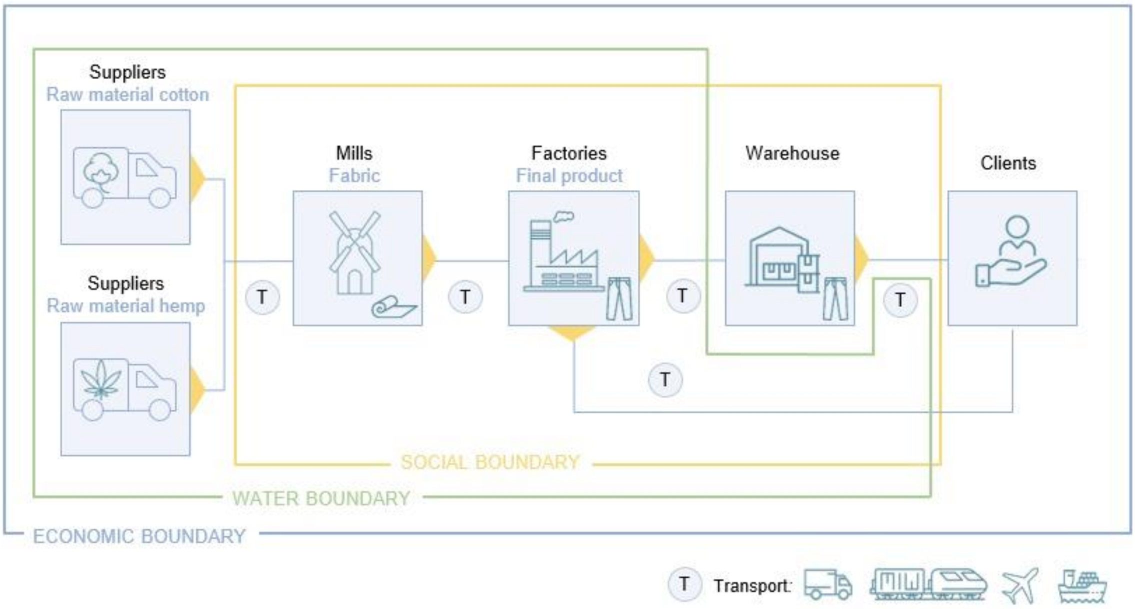

Figure 7: Case study's supply chain representation.

The data collected and used as input in the model was sourced from publicly accessible information. An effort was made to rely, as much as possible, on data made public by an existing apparel company, in annual and sustainability reports, as well as in its official website. Nevertheless, due to lack of available information, several assumptions and estimates, which will be addressed and better described ahead, had to be made.

The location points for the suppliers, mills, factories and warehouses were directly based on the public information regarding part of the network design of a physical company in the apparel industry (Levi Strauss & Co., 2023b). Currently, the company's network has available 12 suppliers, 10 mills, 6 factories, 6 warehouses and provides to 14 clients, all entities based in the Asian continent, except for two suppliers, one in Egypt and one in Austria. The company does not own any of the production facilities nor the warehouses in the network, choosing instead to lease the facilities at the beginning of the time span considered of 5 years. This strategic decision, as the company is still beginning to navigate the Asian market and exploring its requirements, avoids incurring in considerate upfront investments in infrastructures and long-term commitments. In addition, there is a total of 16 airports, 9 seaports and 10 railway stations available. In this supply chain, the freight can be transported through road, rail, air and sea, as is often the case in this industry (ASSTRA, 2023). It was ensured that in every island country integrating the network, there was at least one airport or seaport available, to enable the connection to other countries.

Demand

All production decisions made in the network are done based on the market demand. The 14 clients considered and their respective annual demand of final product, in tons, is shown in Table 2. Due to a lack of information concerning the amount and location of stores in each country, each client's demand considered is the aggregated country's demand. Thus, the location for each client corresponds to the geographical center of the country.

Table 2: Annual demand per client.

	Demand (ton)				
Client / Year	**2023**	**2024**	**2025**	**2026**	**2027**
C1: Cambodia	4.5	5	5.5	6.1	6.7
C2: China	372.9	410.2	451.2	496.3	545.9
C3: India	363.6	400	440	484	532.4
C4: Indonesia	72.2	79.4	87.3	96	105.6
C5: Japan	32.1	35.3	38.8	42.7	47
C6: Malaysia	8.6	9.5	10.5	11.6	12.8
C7: Nepal	7.9	8.7	9.6	10.6	11.7
C8: Pakistan	59.9	65.9	72.5	79.8	87.8
C9: Philippines	29.2	32.1	35.3	38.8	42.7
C10: Singapore	1.5	1.7	1.9	2.1	2.3
C11: South Korea	13.2	14.5	16	17.6	19.4
C12: Sri Lanka	5.6	6.2	6.8	7.5	8.3
C13: Thailand	18	19.8	21.8	24	26.4
C14: Vietnam	25.6	28.2	31	34.1	37.5

Note that each client's annual demand means to represent the entire country's demand of final product, however, the values presented are merely indicative, since there was no available information on this matter. The values presented for 2023 were based on an apparel company's total net revenue and cost of goods sold, associated to the Asian continent (Levi Strauss & Co., 2022). From the sum of these values, a total revenue per client was obtained, considering the population size of each country, having been assumed that population's size is correlated with demand's size. This data was used to estimate reasonable demand quantities in each market.

According to 2017 forecasts, spending by the global middle class in Asia Pacific was expected to increase by 102% from 2020 to 2030, translating to an average of 10% increase per year (Kharas, 2017). Therefore, the forecasted demand's annual growth was assumed to be 10%. It is important to mention that it was acknowledged that this forecast was made prior to the COVID-19 pandemic and the current war in Ukraine, events that caused and ensued significant disruptions in the world's population and economies. Nonetheless, according to Fengler et al. (2022), the global middle class in Asia has recovered strongly from both crises.

The final product's price per country is presented in Table 3.

Table 3: Final product's price per client.

Client	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14
Price (c.u.)	58	142	32	61	114	62	37	21	75	111	190	23	52	50

A real practiced price for a pair of cotton jeans by an American apparel company was considered and the prices presented per country were obtained by multiplying that value with the purchasing parity power (PPP) for each country, for clothing and footwear[2] (The World Bank, 2017).

Suppliers

As mentioned before, the suppliers, mills, factories and warehouses considered were so based on a real apparel company's network. However, in the interest of simplicity, only a few of each type of entity were selected. This selection was made primarily based on the geographical location of the entity, opting for the ones situated in Asia, and on the facility's size, based on the number of workers employed in each of them, opting for the larger-sized facilities. Despite not belonging to Asia, the suppliers in Austria and Egypt were considered as well. The former due to its considerate production and exportation of hemp (FAO, 2021b) and the latter due to its large size and proximity to the Asian continent.

The annual supply capacity of each supplier for each raw material is presented in Table 4, alongside the respective raw material cost.

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[2] Considering US$=1.

Table 4: Suppliers' annual capacity and cost per raw material.

Supplier	Raw material	Maximum Capacity (ton)	Cost (c.u./ton)
S1: Austria	RM1	1 040	3 142
	RM2	200	4 536
S2: Bangladesh	RM1	260	1 334
	RM2	130	3 402
S3: China	RM1	520	2 235
	RM2	100	7533
S4: China	RM1	650	2 235
	RM2	100	753
S5: Egypt	RM1	390	660
	RM2	-	-
S6: India	RM1	1 050	1 144
	RM2	250	3 402
S7: Sri Lanka	RM1	180	1 170
	RM2	-	-
S8: Pakistan	RM1	260	1 151
	RM2	-	-
S9: Pakistan	RM1	325	1 151
	RM2	-	-
S10: Turkey	RM1	680	1 358
	RM2	350	4 137
S11: Vietnam	RM1	260	1 194
	RM2	-	-
S12: Vietnam	RM1	550	1 194
	RM2	-	-

As this case study focuses exclusively on the supply chain of jeans, and the companies in the apparel industry often produce a broad variety of clothing items, the supply and production capacities, addressed ahead, were estimated from various available sources that considered industry figures.

According to Table 4, all 12 suppliers provide Raw Material 1 (RM1), cotton, but only 6 are also suppliers of Raw Material 2 (RM2), hemp. The information on which countries could supply RM2 was sourced from FAO statistics, that provides data on the countries that produce RM2 (FAO, 2021b). Regarding the prices attributed to the raw materials, due to a lack of available information on the actual prices offered by each supplier, some estimates were made. For RM2, the prices per country were collected from a special issue report on industrial hemp (United Nations, 2022) which presented the price per kg, in 2020, for each region of the world. The price of RM1 per country was obtained by multiplying the average global price of cotton between 2020 and 2022 (OECD/FAO, 2023) for each country's price level index[3], in gross domestic product (The World Bank, 2017).

Mills, factories and warehouses

The production process of the final products is represented in Figure 8.

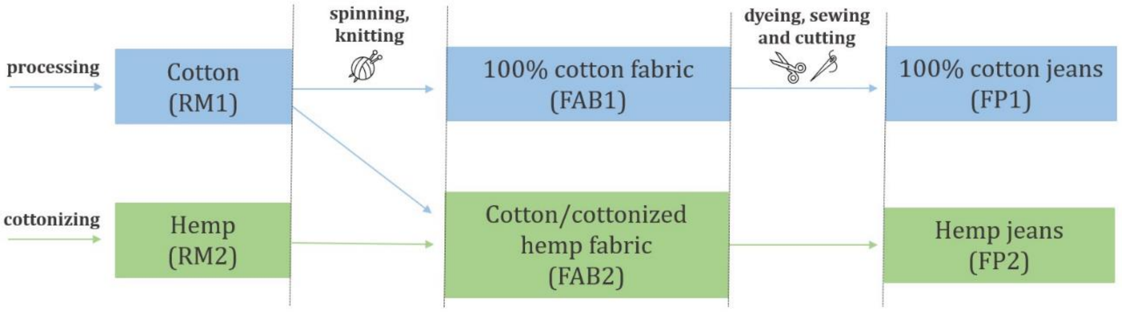

Figure 8: Production process.

The flow of raw material that leaves the suppliers must reach a mill where the transformation of raw material into fabric will take place. The annual production capacity for each mill, that is, the maximum capacity available for the company to lease, is presented in Table 5. There is no allocation of the production's capacity to a single type of fabric, as it was assumed that when it reaches the mill, the RM2 has already undergone a cottonization process, as depicted in Figure 8, making the transformation process into fabric equal for both raw materials. Thus, the capacity requirements to produce both fabrics are identical and there are no restrictions, at the mill, concerning the product-mix. During the considered time period, it is assumed that no raw material stock is kept, therefore the flow that arrives at the mill is immediately transformed into fabric and shipped to a factory.

Although the company only has, in fact, one single expense associated with the leasing of a space, whether it is a mill, factory or warehouse, this total was broken down into the cost groups (lease, production, stock, labor), to facilitate the results analysis.

The lease costs also presented in Table 5, and all that will follow, were a result of estimations. An average cost per entity leased was obtained based on the 2022 annual report of the same company based in the United States (Levi Strauss & Co., 2022). Through the price level index[3], in gross fixed capital a lease cost per country was calculated (The World Bank, 2017).

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[3] The price level index considers World=100.

Table 5: Mills' annual capacity and lease cost.

Mill	Maximum Production Capacity (ton)	Lease Cost (c.u.)
M1: Bangladesh	1200	82 053
M2: China	900	118 735
M3: Egypt	400	61 902
M4: India	900	64 194
M5: India	500	64 194
M6: Pakistan	300	72 641
M7: Pakistan	400	72 641
M8: Turkey	300	68 779
M9: Vietnam	400	72 399
M10: Vietnam	300	72 399

Once the fabric is ready, it must then be transported to a factory for the last stage of production to take place. It is in the factories that the jeans' assembly and finishing is done. The annual production capacity for each factory, made available for the company, can be seen in Table 6. Similar to the mills, there is no specific allocation of the production's capacity for a single final product and there is no stock allowed in factories.

Table 6: Factories' annual capacity and lease cost.

Factory	Maximum Production Capacity (ton)	Lease Cost (c.u.)
F1: Bangladesh	400	82 053
F2: Egypt	200	61 902
F3: India	350	64 194
F4: Pakistan	500	72 641
F5: Vietnam	300	72 399
F6: Vietnam	300	72 399

The full production cost was estimated as 30% of the final product's price. For this calculation, the final product's price was considered as an average price of a pair of jeans. Of this 30%, it was assumed that the fabric production accounted for 60% of the production cost (Kalkanci & Özer, 2018) whereas the remaining 40% was attributed to the final product's assembly in the factories, as well as the costs associated with packaging. Once again, as the transformation process into fabric and from fabric into final product is identical regardless of the raw materials used, there is only one production cost per ton of fabric and per ton of final product. These costs can be consulted in Table 7.

Table 7: Production costs.

Production Facilities	**Production Cost (c.u./ton)**
Mills	1 430
Factories	953

In case of overproduction, the flow of final product that leaves the factories, not necessary to satisfy demand, is directed to a warehouse, the only entity that allows stock of final product. The maximum inventory capacity available for the company to lease, in each warehouse, and the inventory cost are presented in Table 8. The inventory cost was estimated to be 10% of the final product's average price, mentioned above. It was also considered, for this case study, an initial inventory of zero.

Table 8: Warehouses' annual capacity, lease costs and inventory costs.

Warehouse	**Maximum Inventory Capacity (ton)**	**Lease Cost (c.u.)**	**Inventory Cost (c.u./ton)**
W1: Bangladesh	1 000	82 053	794
W2: China	1 000	118 735	
W3: India	1 000	64 194	
W4: Sri Lanka	1 000	75 899	
W5: Pakistan	1 000	72 641	
W6: Vietnam	1 000	72 399	

The bill of materials (BOM) for each raw material, fabric and final product is presented in Table 9.

Table 9: Bill of materials.

Product	RM1	RM2	FAB1	FAB2	FP1	FP2
RM1	1	-	1.175	0.8225	-	-
RM2	-	1	-	0.3525	-	-
FAB1	-	-	1	-	1.32	-
FAB2	-	-	-	1	-	1.32
FP1	-	-	-	-	1	-
FP2	-	-	-	-	-	1

The manufacturing of a pair of jeans, depending on the product's composition and production process, undoubtedly requires a substantial amount of resources, from electricity to a very assorted set of chemicals. For simplicity reasons, and given the decisions to be analyzed, the model presented only considered the raw material per se as the production input. According to Sarı et al. (2023), the cotton consumed to produce 1 ton of fabric, in this case FAB1, is 1.175 ton. As for the hemp jeans, a composition with a 70/30 cotton-to-cottonized hemp blend was considered (Levi Strauss & Co., 2023a), and it was assumed that the total raw material required to produce 1 ton of fabric, in this case FAB2, was 1.175 ton as well. Finally, it was assumed that to produce 1 pair of jeans, whether FP1 or FP2, it is necessary 1.5 yards of fabric, which weighs approximately 0.594 kg (Szabo, 2023). Thus, to produce 1 ton of 0.45 kg jeans, 1.32 ton of fabric is required.

Fundamental in the operation activities in the mills, factories and warehouses, are the employees that produce and manage the different products circulating in the supply chain. The number of workers necessary to handle 1 ton of final product in the warehouse, to produce 1 ton of fabric and to produce 1 ton of final product are displayed in Table 10.

Table 10: Number of workers necessary in warehouses, mills and factories.

	Warehouse	**Mill**	**Factory**
Workers/ton of product	4	0.1	1

These values were calculated based on public information regarding mills, factories and warehouses within the textile industry, that specialize in the production of jeans. To obtain the workforce necessary, the division between the annual production output of these companies and the quantity of workers employed was calculated. As far as the compensation for these workers is concerned, despite not being effectively employed by the company, it still constitutes an expense the company takes on. The annual labor costs are displayed in Table 11.

Table 11: Annual labor costs.

Country	**Labor Cost (c.u.)**
Bangladesh	1 680
China	12 000
Egypt	2 112
India	2 376
Pakistan	1 620
Sri Lanka	1 992
Turkey	4 872
Vietnam	3 456

The data was retrieved from a dataset compiled by the International Labour Organization (ILO) that presented the average monthly earnings of employees by sex and economic activity, later converted into annual earnings (ILO, 2022).

Transportation related parameters

The airports, seaports and railway stations mentioned above, and their respective annual hub cost, can be consulted in Table 12.

Table 12: Annual hub costs.

Transport Infrastructure (Airport (A), Seaport (SP), Railway Station (R))	**Hub Cost (c.u.)**
A1: Austria	289 476
A2: Bangladesh	67 657
A3: Cambodia	96 351
A4: China	121 670
A5: Egypt	35 868
A6: India	70 329
A7: Indonesia	86 083
A8: Japan	346 583
A9: Malaysia	96 211
A10: Pakistan	76 659
A11: Philippines	91 991
A12: South Korea	167 384
A13: Sri Lanka	72 580
A14: Thailand	71 877
A15: Turkey	134 470
A16: Vietnam	94 804
SP1: Bangladesh	67 657
SP2: Cambodia	96 351
SP3: China	121 670
SP4: China	121 670
SP5: India	70 329
SP6: Indonesia	86 083
SP7: Pakistan	76 659
SP8: Sri Lanka	72 580
SP9: Vietnam	94 804
R1: Bangladesh (Dhaka)	67 657
R2: Bangladesh (Chittagong)	67 657
R3: China (Shenzhen)	121 670
R4: China (Shanghai)	121 670
R5: India (New Delhi)	70 329
R6: India (Mumbai)	70 329
R7: Pakistan (Karachi)	76 659
R8: Pakistan (Faisalabad)	76 659
R9: Vietnam (Ho Chi Minh)	94 804
R10: Vietnam (Ha Noi)	94 804

The hub fixed costs displayed were obtained by assuming a hub cost for France (Mota et al., 2018) and considering France's price level index[4], specific for transport services (The World Bank, 2017). Then, through the price level index, for transport services in each country, their respective hub cost was obtained.

As for the transport requirements of the supply chain, the company relies on an outsourcing strategy. Considering the extensive geographical footprint of its supply chain and the location of its clients, the company also counts on transport by truck, train, plane and boat. The transportation costs for each transport mode were calculated similarly to the hub costs and are presented in Table 13, per country.

Based on a study carried out by the research institute Panteia (2023), the total cost per ton-km for each freight transport mode was obtained, for the Netherlands. Following the method used to calculate the hub costs, the transportation costs were obtained for each country of the supply chain where a flow could originate.

Table 13: Transportation costs.

	Transportation Cost (c.u./tkm)			
Country/Transport Mode	Road	Rail	Air	Sea
Austria	0.38	0.014	0.18	0.0032
Bangladesh	0.09	0.003	0.04	0.0008
Cambodia	0.13	0.005	0.06	0.0011
China	0.16	0.006	0.08	0.0014
Egypt	0.05	0.002	0.02	0.0004
India	0.09	0.003	0.04	0.0008
Indonesia	0.11	0.004	0.05	0.0010
Japan	0.45	0.016	0.21	0.0039
Malaysia	0.12	0.005	0.06	0.0011
Pakistan	0.10	0.004	0.05	0.0009
Philippines	0.12	0.004	0.06	0.0010
Singapore	0.23	0.009	0.11	0.0020
South Korea	0.22	0.008	0.10	0.0019
Sri Lanka	0.09	0.003	0.04	0.0008
Thailand	0.09	0.003	0.04	0.0008
Turkey	0.17	0.006	0.08	0.0015
Vietnam	0.12	0.004	0.06	0.0011

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[4] The price level index considers World = 100.

The number of workers necessary for each transport mode per ton-km are presented in Table 14.

Table 14: Number of workers necessary per transport mode.

	Road	Rail	Air	Sea
Workers/tkm	2.67	15.56	0.07	11.59

The quantity of workers considered represent the division between the total amount of ton-km of transported freight in 2020 in the United States (Bureau of Transportation Statistics, 2020) and the respective number of employments in each transportation sector (Bureau of Labor Statistics, 2023).

Distances

The distances between the entities were calculated through the application of the Euclidean distance formula, making use of each entity's coordinates. This approach assumes a straight-line distance between two points.

Water related parameters

Water is involved in various stages of the supply chain, and it is crucial to measure its impact in order to find solutions to reduce its consumption. To do so, three different indicators were employed: water stress (of a region), water footprint (of raw materials), water consumption (for fabric and final product's manufacturing and transport activities).

The water stress indicator corresponds to the environmental indicator 6.4.2 built and used by FAO of the United Nations. According to FAO (2021a), "This indicator measures the level of water stress by providing an estimate of the pressure exerted by all economic sectors on the country's renewable freshwater resources.". The percentual level of water stress measured by FAO (2022) for the countries present in this supply chain is summarized in Table 15.

Table 15: Water stress level per country.

Country	Water Stress (%)
Austria	9.64
Bangladesh	5.72
Cambodia	1.04
China	41.52
Egypt	141.17
India	66.49
Indonesia	29.70
Japan	36.05
Malaysia	3.44
Pakistan	116.31

Table 15: Water stress level per country. (Cont.).

Country	Water Stress (%)
Philippines	26.25
South Korea	85.22
Sri Lanka	90.79
Thailand	23.01
Turkey	45.17
Vietnam	18.13

It is worth mentioning that other indicators to measure the water stress of a region were considered, in particular Aqueduct's water stress (World Resources Institute, 2023). Both indicators track the physical availability of freshwater resources by measuring the ratio of total freshwater withdrawal to the available and renewable freshwater resources. An advantage of the Aqueduct's indicator relies on its granular data, which allows to obtain the water stress for any location in the world, provided there is available data for the region. This showed that one country could present different levels of water stress. FAO's indicator, on the other hand, presents a single water stress per country. It is also noted in the indicator's limitations that Aqueduct is tailored to large-scale comparisons, and one should consider its limited added value on a local level (Hofste et al., 2019). Ultimately, the indicator 6.4.2 from Aquastat was chosen due its more comprehensive take. Unlike Aqueduct, the calculation for the available freshwater resources in Aquastat accounts for, by subtracting, the environmental flow requirements (FAO, 2021a).

The water footprint for RM1 (cotton) and RM2 (hemp) per supplier are showcased in Table 16.

Table 16: Raw material's water footprint.

	Water Footprint (m^3/ton)	
Supplier / Raw Material	RM1	RM2
S1	4 267	724.5
S2	4 267	724.5
S3	2 398	2 183.1
S4	2 398	2 183.1
S5	4 457	-
S6	9 724	754.6
S7	4 267	-
S8	5 954	-
S9	5 954	-
S10	3 509	5 991.9
S11	4 267	-
S12	4 267	-

The study by Chapagain and Hoekstra (2005), in which the values considered for the water footprint of cotton were based on, distinguishes between the three types of water use, previously mentioned: blue water, for the withdrawal of water for irrigation or processing, green water, for the evaporation of infiltrated rainwater for cotton growth, and grey water for the volume of water necessary to dilute the pollution generated from the crop's cultivation. Due to this blue, green and grey water measure's specifications, it proved to be vital that the water footprint data was disaggregated on a per-country basis, since each country's climate, soil and agricultural practices are important factors to consider. The cotton's water footprint presented represents the sum of the blue, green and grey water required to produce, in each country, 1 ton of seed cotton. Note that the study used did not include every country, therefore, for the missing data, the global average value of blue, green and grey water had to be assumed (Chapagain and Hoekstra, 2005).

As for the raw material hemp, less information was available regarding its water footprint. Nonetheless, with the intent of establishing a fair comparison between both raw materials, an effort was made to obtain values that considered the same water impact as the one considered for cotton's water footprint. The blue, green and grey water values for hemp's growing stage, per country, were calculated by Averink (2015), in a study conducted under the guidance of Prof. A.Y. Hoekstra. For the few supplier countries that lacked information on their blue, green and grey water impact, it was not possible to complete the gaps with the global average, as it was not available. For these cases, correspondent to S2 in Bangladesh and S6 in India, some research was conducted to obtain the predominant soil type of the countries. This parameter was considered a proxy between countries, and Bangladesh's water footprint was assumed to be equal to Austria's water footprint while India's was assumed to be equal to Chile's. According to Averink (2015), Austria presents a predominantly sandy loam soil, which is also very present in the region of Dhaka in Bangladesh (Islam et al., 2017), where S2 is situated. As for Chile, Averink assumes a predominantly clay loam soil which was found to be very similar to the soil of the land in Gujarat (Solanki et al., 2021), where S6 is located. The parameter soil was chosen as a proxy instead of climatic conditions because, according to Averink (2015) and Mekonnen & Hoekstra (2011) the blue water attributed to raw material hemp is zero, as the production and yield of hemp does not increase with irrigation.

Lastly, the water consumption values used for the production stages is presented in Table 17. As it was stated before, it was assumed that the transformation process into fabric and final product is equal for both raw materials. For this reason, it was also assumed that the water requirements for both production stages are the same, despite the type of product being fabricated.

Table 17: Product's water consumption.

	Fabric	**Final Product**
Water Consumption (m^3/ton)	780.9	390.4

The water consumed in the production of fabric and final product was based on a LCA conducted by Levi Strauss & Co. (2015) on a pair of jeans Levi's® 501®. According to this study, 68% of water consumption was related to the raw material's fiber, 6% came from the fabric production and 3% derived from the garment assembly and finishing, as well as the sundries application and packaging. The last impact was attributed to consumer care, which is not within the scope of the present work, thus it was disregarded. The sum of these three contributions was equaled to the total water footprint of a finished textile product of cotton, including the blue, green and grey water (Chapagain & Hoekstra, 2005). The value indicated for the water consumption, in Table 17, for the fabric represents 6% of this calculated total water footprint and the final product represents 3%.

As for the water consumption associated with the transports, the midpoint category Water Consumption of the method ReCiPe 2016 available in Simapro was used. The values considered are displayed in Table 18. The references used for each type of transport mode will be detailed ahead.

Table 18: Transport mode's water consumption.

	Road	**Rail**	**Air**	**Sea**
Water Consumption (m^3/tkm)	5.09×10^{-3}	8.34×10^{-5}	3.42×10^{-4}	7.01×10^{-6}

Environmental characterization

The characterization of the environmental impact of each stage of the supply chain was done through Simapro Ecoinvent 3 database version 9.3.0.3.

For the raw material's crop cultivation and respective treatment stage, two different raw materials were identified. For cotton, the reference "Yarn, cotton {IN}| yarn production, cotton, ring spinning | Cut-off, U" was used, and the impacts are modelled according to Indian data. For hemp, due to a lack of information in the Simapro database regarding hemp fiber production, the reference "Yarn, jute {BD}| yarn production, jute | Cut-off, U" was used. According to La Rosa and Grammatikos (2019), jute and hemp are very similar plants, therefore one can expect their impacts to resemble each other. Once again, the reference relies on an Asian based country's data, Bangladesh.

For the production activities in the supply chain, two references, regarding processes, were considered: "Bleaching and dyeing, yarn {IN}| bleaching and dyeing, yarn | Cut-off, U" and "Finishing, textile, woven cotton {GLO}| finishing, textile, woven cotton | Cut-off, U}. Given that it was assumed that the manufacturing of fabric and final product is the same, regardless of the type of final product being produced, it was reasonable to assume as well that the impacts associated to the production are equal. An effort was made to select references that would not consider the same processes in their network, to avoid the double, and inaccurate, tally of an impact.

Finally, the impacts related to the transportation operations of the supply chain were also considered through the following references: for air transport "Transport, freight, aircraft, medium haul {GLO}| transport, freight, aircraft, dedicated freight, medium haul | Cut-off, U", for rail transport "Transport, freight train {IN}| transport, freight train, diesel | Cut-off, U", for road transport "Transport, freight, light commercial vehicle {RoW}| processing | Cut-off, U" and for sea transport "Transport, freight, sea, container ship {GLO}| transport, freight, sea, container ship | Cut-off, U".

The environmental impacts are divided into eighteen midpoint categories, presented in Table 19, alongside the code, that will be used to reference them, from this point onwards. For the normalization factors for each midpoint category, Table 32 in Appendix can be consulted.

Table 19: Midpoint categories and codes.

Midpoint Category	Code
Global warming	GW
Stratospheric ozone depletion	SOD
Ionizing radiation	IR
Ozone formation, Human health	OFHH
Fine particulate matter formation	FPMF
Ozone formation, Terrestrial ecosystems	OFTE
Terrestrial acidification	TA
Freshwater eutrophication	FEU
Marine eutrophication	MEU
Terrestrial ecotoxicity	TE
Freshwater ecotoxicity	FEC
Marine ecotoxicity	MEC
Human carcinogenic toxicity	HCT
Human non-carcinogenic toxicity	HNCT
Land use	LU
Mineral resource scarcity	MRS
Fossil resource scarcity	FRS
Water consumption	WC

Note that the ReCiPe 2016 also offers an indicator for water consumption. Nonetheless, this indicator did not provide the granularity that this study sought out for the supply chain activities under analysis.

Other parameters

Additional economical parameters were considered: a tax rate of 30% and an interest rate of 10%.

4.2 Scenarios

The case study was assessed under three different demand scenarios, following a stochastic approach. Every case considers a time span of 5 years, with yearly time periods; however, the expected demand increase is different for each case. Amidst the present era of heightened instability and rapid change, it is imperative for companies to be well prepared for different contingencies. Studying the variability in the demand is a useful tool to achieve this promptness and to acquire a deeper understanding of the potential risks and opportunities the company can face.

The current forecast for the increase in demand is 10% per year. This value was solely assumed for the base scenario, whereas the remaining two contemplate a more optimistic scenario, where this rate is double the expected, and a more pessimistic one, where the demand increases at a lower rate. The three scenarios considered, and its respective specifications, are presented in Figure 9.

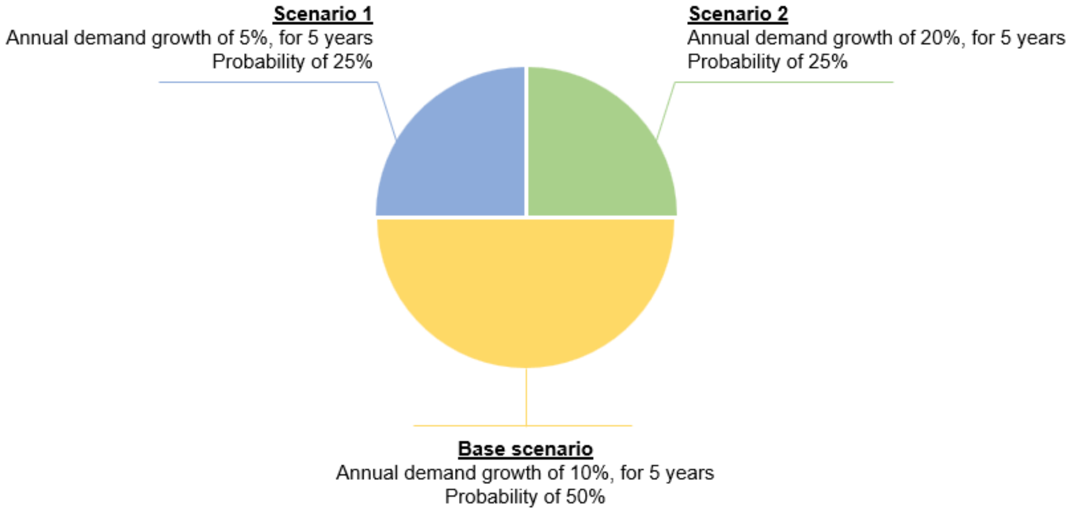


Figure 9: Stochastic analysis' scenarios.

The mathematical model had to suffer some adjustments for this scenario analysis. A new index s (for scenario) was computed and added to the decision variables X_{pijtk}, S_{pik} and W_{pik}, and to all the auxiliary variables created. A new parameter to define the probabilities for each scenario ($prob_s$) was created as well. The model's constraints were then modified accordingly and the new equations of the three objective functions, representing the economic, water impact, and social dimensions are given by expressions (41), (42) and (43), respectively.

$$\max NPV = \sum_{s \in S} prob_s \cdot \left(\sum_{k \in K} \frac{CashFlow_{ks}}{(1+ir)^k} \right) \tag{41}$$

$$\min WaterImpact = \sum_{s \in S} prob_s \cdot \Big(\sum_{k \in K} \sum_{P \in P_{rm}} WaterImpact\_RM_{pks} + \sum_{k \in K} \sum_{P \in P_{fab}} WaterImpact_{FAB_{pks}} + \sum_{k \in K} \sum_{P \in P_{fp}} WaterImpact_{FP_{pks}} + \sum_{k \in K} \sum_{t \in T} WaterImpact_{Trans_{tks}} \Big) \tag{42}$$

$$\max JobCreation = \sum_{s \in S} prob_s \cdot \Big(\sum_{\substack{(p,i,k):(p,i) \in (V_{mfab} \cup V_{ffp}) \\ k \in K}} \frac{W_{piks} \cdot w_i}{ny} + \sum_{\substack{(p,i,k):(p,i) \in (V_{wfp}) \\ k \in K}} \frac{S_{piks} \cdot w_i}{ny} + \sum_{\substack{(t,p,i,j,k):(p,i,j) \in NetCon \\ k \in K \\ t \in T}} \frac{X_{pijtks} \cdot w_t \cdot dist_{ij}}{ny} \Big) \tag{43}$$

5 – Results Analysis

The following chapter focuses on the results obtained from the implementation of the developed mathematical model to the presented case study.

With the intent of understanding how the supply chain under analysis is influenced by each of the three sustainability pillars, measured through the objective functions previously described, five main cases were considered (A-E). Cases A, B and C focus on a supply chain that only produces FP1. Case A prioritizes the optimization of the economic function, followed by the water and the social functions, respectively. Case B prioritizes the optimization of the water impact objective function over the economic one, and case C does the same, only it requires a non-negative value for the latter. Cases D and E focus on a supply chain that produces both FP1 and FP2. Case D, like case A, prioritizes the objective functions in the order: economic, water impact and social; and case E, like case C, prioritizes the water impact over the economic function, while requiring a non-negative value for the cash-flows generated.

The chapter is structured as follows. In Section 5.1 the execution framework is presented. In Section 5.2 the cases analyzed intend to respond to the first research question formulated, by examining the extent to which the current supply chain can be adjusted to face the expected increase in pressure on the available water resources. In Section 5.3 a similar analysis is conducted, now focusing on a supply chain that includes hemp as a raw material. In addition, a comparative analysis between both supply chains is made. Section 5.4 and 5.5 take a closer look to the social and overall environmental impact, respectively, of these supply chains. Section 5.6 comprises a stochastic analysis, where demand uncertainty is analyzed. Finally, Section 5.7 presents recommendations to the company’s decision makers based on the integrated approach taken throughout the chapter.

5.1 Execution framework

To implement the model detailed in chapter 3 and solve the problem presented in chapter 4, the General Algebraic Modeling System (GAMS) was employed. Specifically, the GAMS version 42.4.0 on an 11th Gen Intel(R) Core(TM) i5-1135G7 @ 2.40GHz with 8 GB of RAM. Some adaptations to the generic model previously presented were required in order to analyze specific scenarios, intrinsic to the case study under scope.

5.2 Exclusively cotton products – obtained supply chain structure

The following cases A, B and C take into consideration a supply chain in which there is only the production of 100% cotton jeans (FP1).

5.2.1 Single objective optimization

In this section, the analysis will be focused on single objective optimizations to lay down the basis that will allow a better understanding of the complex trade-offs that will expectedly emerge. Only with this understanding, can the final network design and operations related decisions be made.

Cases A and B

The results for cases A and B were obtained following a lexicographical approach that required ordering the objective functions from least to most important, considering the company's priorities.

For case A, the NPV value obtained translates the maximum economic performance the company can achieve, and the water impact value corresponds to the lowest the company can attain while maintaining that same NPV. Case B delivers the highest NPV value the supply chain can reach while maintaining the lowest water impact possible. For each case, the solution for the social objective function is the highest value attainable while maintaining the NPV and water results already obtained. By employing this method, only efficient and non-dominated solutions are presented, that is, the improvements obtained in one objective function do not compromise the optimality of the objective functions' values previously calculated. The results for each objective function, for both cases, are shown in Table 20.

Table 20: Single optimization results - case A and B.

	NPV (c.u.)	**Water Impact**	**Jobs Created (per year)**
Case A	6.21×10^7	6.35×10^7	1.06×10^7
Case B	-4.44×10^7	6.01×10^6	8.65×10^7

As observed, the findings are remarkably different, with the variation between both NPV results displaying a striking contrast. From case A to case B, the NPV suffers a reduction of 172%. Not only this, but it delivers a negative outcome. It is acknowledged that this NPV solution is not a sustainable one for the company and, therefore, is not recommended. Nonetheless, the analysis of this scenario was found to be valuable to validate the model, guaranteeing that the restrictions imposed were being respected. In addition, there is a reduction of 91% from case A's water impact to case B's thus, making sense of the motives behind the decisions taken in case B will benefit the decision maker's grasp on potential strategies to minimize the supply chain's water impact. It is important to emphasize that the water impact analyzed here comprises both the supply chain's water consumption, in m^3, and the impact associated with the geographical region where that water consumption takes place, measured by its water stress index level, a percentage. For this reason, the water impact is dimensionless, and should only be used for comparison purposes. Case A's water impact of 6.35×10^7 corresponds to a water consumption of 8.17×10^7 m^3, whereas case B's water impact of 6.01×10^6 involves the consumption of 5.00×10^7 m^3 of water, a difference of 39%. Finally, the difference between the social objective function is by far the highest, the quantity of jobs created per year increasing by 717% from case A to case B.

Given that the company's economic goals are its priority, case A's solution will take a central role in the developed analysis. The superstructure obtained for this case is illustrated in Figure 10.

Figure 10: Network design – case A.

In case A, Figure 10 shows that 3 mills, located in Bangladesh (M1), Egypt (M3) and India (M4) are leased and supplied by 5 different suppliers. Of these, 3 are from the same country where the mills are situated (S2, S5, S6) and the remaining 2 from Pakistan (S8 and S9).

Given that the production cost is equal in every mill, the decision on which mills to lease is mainly influenced by the lease, the hub, the labor and the transport costs. The decision to lease M1, unlike the decision to lease M3 and M4, was not primarily influenced by the lease cost, which is, in fact, the second highest, only behind China. It was instead predominantly influenced by the labor costs as well as its strategic position in the network. Compared to China, the labor costs in Bangladesh are six times lower. In addition, albeit pushing the lease costs upward, it proves itself to be more cost-effective to have a mill in this location, in a more centralized position, as it drives transport costs down. It is also worth remarking that Sri Lanka (S7) offers better raw material prices than Bangladesh (S2), however, to reach M1, or any mill for that matter, the company would need to incur in considerate hub costs to transport the raw material by boat or plane from Sri Lanka to the continent. It is also due to these substantial hub costs that the main transport mode used in this solution is the truck. The only exception, when transport by air is used, occurs when the final products must reach the clients located in islands (C4, C5 and C9). Finally, the factories leased in this solution are in Bangladesh (F1), Egypt (F2), India (F3) and Pakistan (F4).

The superstructure obtained for case B is depicted below in Figure 11.

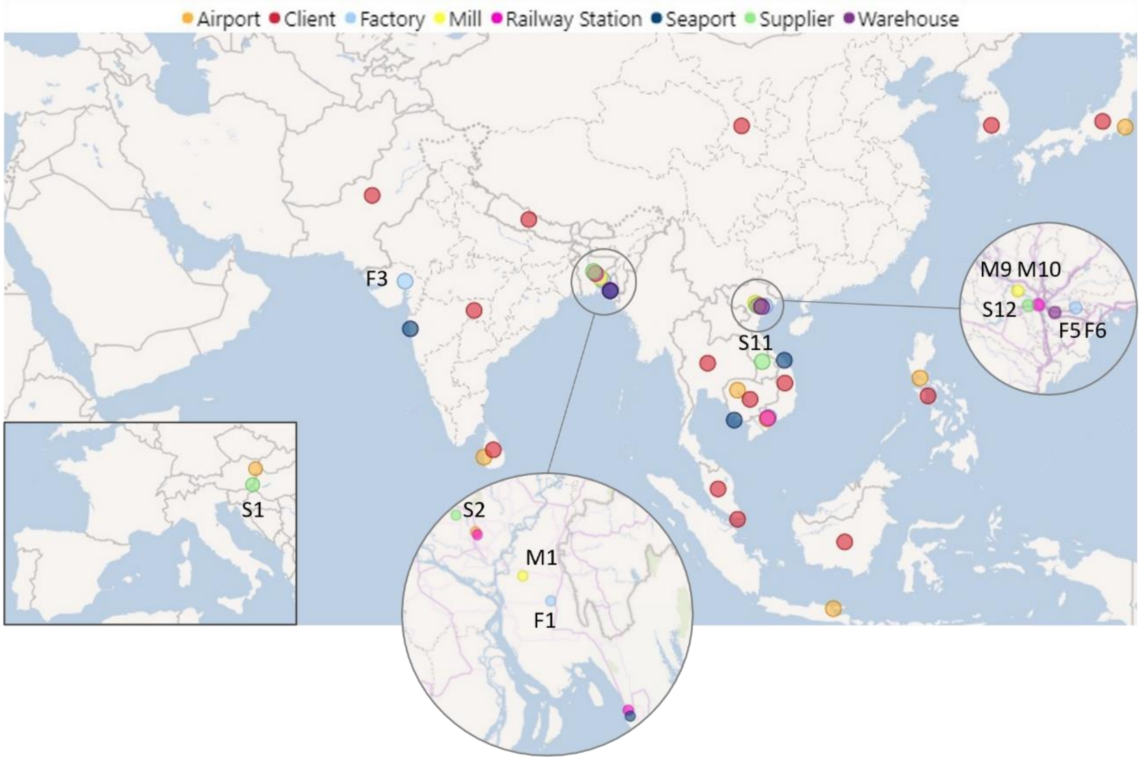


Figure 11: Network design – case B.

For case B, when the decisions are made to minimize the supply chain's water impact, the network structure obtained is notably different. Based off an immediate observation of Figure 11, comparatively to Figure 10, it is observed that the network is composed of more entities, more condensed in the Indochinese peninsula and in Bangladesh. Additionally, the network extends to Europe, where a new supplier is located, and an airport is used.

Nonetheless, similar to case A, 3 mills are leased, now situated in Bangladesh (M1) and Vietnam (M9 and M10). The supply of raw material to those mills is ensured by 4 suppliers, one in Austria (S1), one in Bangladesh (S2) and two in Vietnam (S11 and S12). Driven now by the need to minimize the impact of water, and disregarding the costs associated with its decisions, the suppliers are chosen based on the water stress of the supplier's location and its raw material's water footprint. Although the suppliers in China and Turkey have lower water footprints than the chosen ones, they also present a much higher level of water stress, 42% and 23%, respectively. In contrast, the water stress of Austria, Bangladesh and Vietnam are, respectively, 10%, 6% and 18%. These are the lowest water stress levels of all the suppliers available.

There is also an overall preference for the use of boat and train, the former being the least water intensive transport mode and the latter a close second. The factories leased in this case stand in Bangladesh (F1), India (F3) and Vietnam (F5 and F6), the 3 locations with the lowest level of water stress.

Leased Factories' Capacities and Inventory Decisions

The factories' annual capacity used, in cases A and B, is presented in Figure 12.

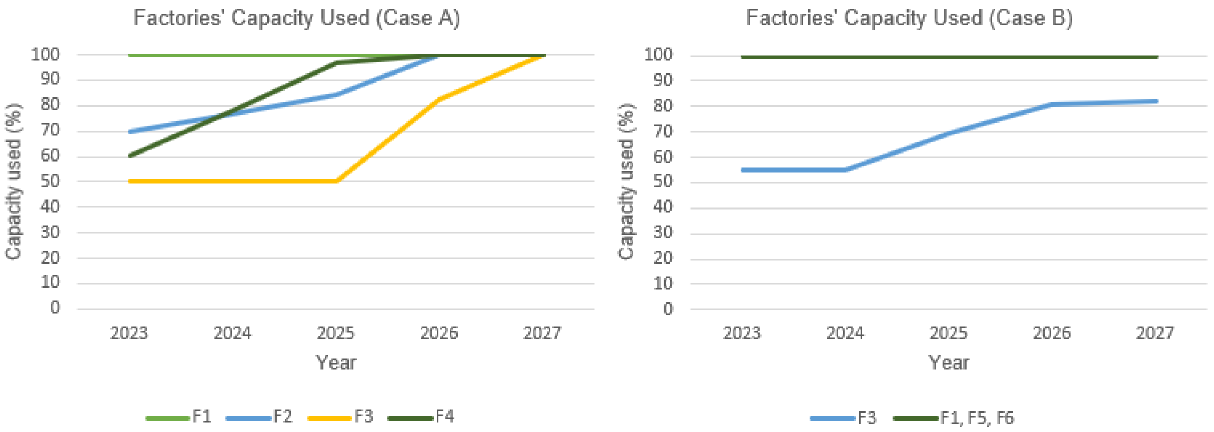


Figure 12: Factories' annual used capacity (case A on the left and case B on the right).

For case A, the last year exhibits all factories being used at full capacity. F1 is constantly used at 100% capacity, F2 and F4 reach their maximum in 2026 and F3 in 2027. From the figure, it can be observed that there is a clear tendency to increase production throughout the years, due to the rise in demand.

For case B, however, F1, F5 and F6 are constantly operating at 100%. Unlike case A, F3 never reaches 100% of its production capacity. This is a direct result of the decisions made regarding the production of stock, which will be further explained ahead.

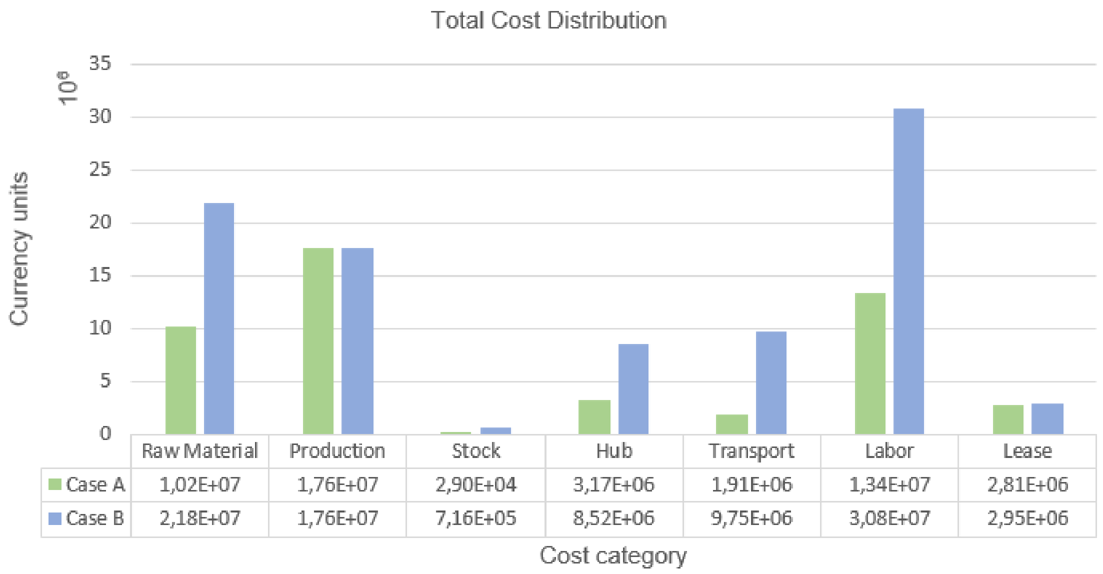
In case A, only one warehouse is leased, the one in Pakistan (W5), which is needed in the fourth year, to store final product that will be necessary to meet the last year's demand. Instead of adding the lease of an extra factory in its 5-year contract, only for the 2027's demand to be met by production made in that same year, it was more profitable for the company to create stock in the previous year and incur in the associated costs. These costs include the inventory costs, the lease cost for W5 and a new set of labor costs, which are the lowest in Pakistan.

On the other hand, in case B, the leased warehouse is located in Vietnam (W6). Given that, in this case, the company's costs are not restrictive, there is creation of stock right at the first year, and it extends up until 2027. This explains why there are three factories operating at 100% from the start and why, when compared to case A, the production in 2027 is lower. Part of the last year's demand is fulfilled by the stock created in the previous years.

Although the demand is being satisfied, it should be noted that having all factories operate at 100% capacity is not desirable or sustainable in the long term. It does not provide a buffer for demand variability, nor flexibility in case of unexpected occurrences, which is a protection against possible bottlenecks that can affect lead times and customer satisfaction.

Costs

Proceeding now to the costs' analysis, Figure 13 illustrates the distribution of costs for both cases.



	Raw Material	Production	Stock	Hub	Transport	Labor	Lease
🟩 Case A	1,02E+07	1,76E+07	2,90E+04	3,17E+06	1,91E+06	1,34E+07	2,81E+06
🟦 Case B	2,18E+07	1,76E+07	7,16E+05	8,52E+06	9,75E+06	3,08E+07	2,95E+06

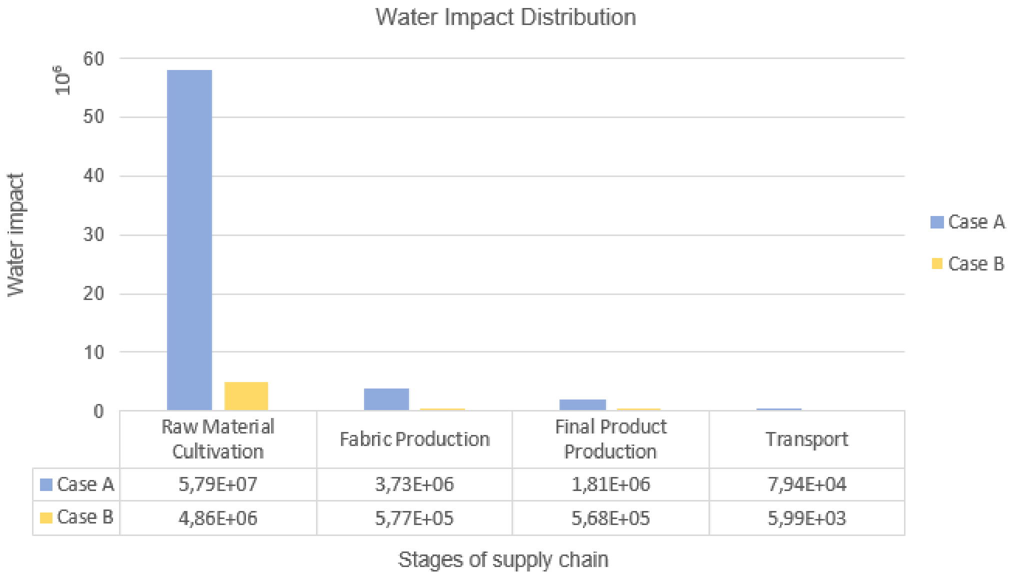
Figure 13: Total cost distribution – cases A and B.

There are notably three major costs in this distribution, that together, for case A, make up more than 80% of the company's total cost. The largest, representing 1.76×10^7 c.u. (36% of total cost), belongs to the production operations, the second highest, 1.34×10^7 c.u. (27% of total cost), is attributed to labor costs and it is closely followed by the raw material costs, which corresponds to 1.02×10^7 c.u. (21% of total cost). Based on the results for solution A, the large portion attributed to labor in the company's cost structure justifies that the decisions made in the network, mentioned above, have an overall tendency to produce in locations where they can have lower workforce expenses.

In comparison, for case B, the most significant cost is the labor cost of 3.08×10^7 c.u. (33% of total cost), followed by the raw material cost (24% of total cost) and the production cost (19% of total cost). Since it is not maximizing the NPV, the labor costs are now 2 times higher, comparatively to case A, and almost 2 times higher than case A's highest cost. Another major difference between the two cases pertains to the transport costs, which are more than 5 times larger in case B.

Water Impact

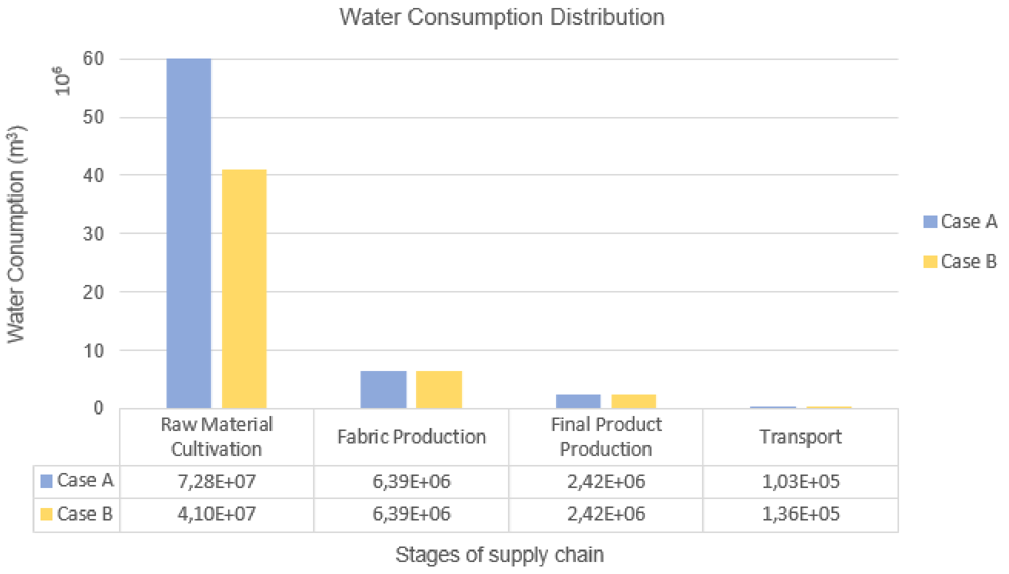
Analyzing now the water impact in each case, Figure 14 allows for the visualization of the water impact's distribution between the different stages of the supply chain.



	Raw Material Cultivation	Fabric Production	Final Product Production	Transport
Case A	5,79E+07	3,73E+06	1,81E+06	7,94E+04
Case B	4,86E+06	5,77E+05	5,68E+05	5,99E+03

Figure 14: Water impact distribution – case A and B.

It is clear from the analysis that the water impact associated with the raw material production is the most prevalent factor influencing the supply chain's water impact, accounting for 91% of total water consumed in case A and 81% in case B. The contribution's hierarchy displayed in the results matches the theoretical research mentioned in Section 4.1, regarding the most water intensive stages in the industrial textile supply chain. However, since the water impact assessment considers both the water consumption and the water stress level of the region where the water is in fact consumed, a more in-depth water analysis was required. Figure 15 expresses the water consumed in each stage of the supply chain, disregarding the water stress factor.



	Raw Material Cultivation	Fabric Production	Final Product Production	Transport
Case A	7,28E+07	6,39E+06	2,42E+06	1,03E+05
Case B	4,10E+07	6,39E+06	2,42E+06	1,36E+05

Figure 15: Water consumption distribution – case A and B.

According to Figure 15, the water consumed for the cultivation of raw materials between case A and case B displays a much smaller difference than the one presented in Figure 14. Nonetheless, case B still showcases a lower consumption in this stage than case A. This means that, although the water practices adopted by each supplier can have a positive impact on the water consumption, evidenced by the decrease seen from case A to case B in Figure 15, the water stress of the location where the cultivation is done also plays a substantial role in the reduction of this impact, evidenced by the significant difference between case A and B in Figure 14.

For both fabric production and final product production, it can be observed that the water consumed is the same in both cases. That is expected since the demand for final fabric and final product does not vary between cases, thus nor do the production's water requirements. This means that the improvement in water impact in both stages is exclusively influenced by the water stress level of the regions where the production takes place. Finally, the transportation activities require more water in case B than in case A. Given that in Figure 14 it was clear that the water impact was significantly lower in case B, it can be deduced that the water impact is heavily influenced by the water stress level of the regions where these activities occur.

Case C

As stated before, a third case was analyzed, case C. In this new scenario, the optimization goal was to minimize the water consumption of the supply chain while setting up the cash-flow per year as a non-negative value. The solution obtained is presented in Table 21.

Table 21: Single optimization results – case C

	NPV (c.u.)	**Water Impact**	**Jobs Created (per year)**
Case C	0	6.66×10^6	1.73×10^7

Although still not an economically viable option for the company, as it does not deliver a positive NPV, the analysis of this case will provide results for better and more realistic comparisons with case A than the ones case B would be able to provide.

The network superstructure of case C can be consulted in Figure 16.

Figure 16: Network design – case C.

The main takeaways, and differences from case B, concern the suppliers, the factories and the transport modes used. Compared to case B, and according to Figure 16, there is the addition of one supplier, in China (S3), and the lease of the factory in Pakistan (F4) instead of the factory in India (F3). Both decisions are a direct result of the annual restriction to deliver non-negative cash-flows. Purchasing the raw material from S3 in the last two years, which is the next best unused supplier when it comes to water consumption minimization, occurs due to its lower prices comparatively with the other suppliers used in the network (S1, S2, S11, S12). Also, opting for F4 over F3, the latter having a lower water stress level, is due to the labor costs in Pakistan being lower than in India, 1 620 c.u. against 2 376 c.u..

Finally, moving the products by sea or rail, proved to be too costly because of the associated hub costs. Thus, most flows in this network are done by truck, the transport mode that requires the most water. Nonetheless, like case B, the plane is still more used when compared to case A, but only when the company can “afford” to choose a less water intensive transport.

Water Impact

The water results obtained for the three cases are summarized in Table 22.

Table 22: Water results – case A, B and C

	Case A	**Case B**	**Case C**
Water Impact	6.35×10^{7}	6.01×10^{6}	6.66×10^{6}
Water Consumption (m^3)	8.17×10^{7}	5.00×10^{7}	4.97×10^{7}

The water impact for case C, as expected, falls between the results for case A and B, and it corresponds to a water consumption of 4.97x10^{7} m^{3}. However, case C's water impact result is only 11% higher than the minimum value the water objective function can deliver (case B), whereas it is 90% lower than case A's impact. Moreover, although the water impact increases from case B to case C, the water consumed decreases by 2.30x10^{5} m^{3}.

Figure 17 translates the percentual variation of water impact between case B and C for each stage in the supply chain.

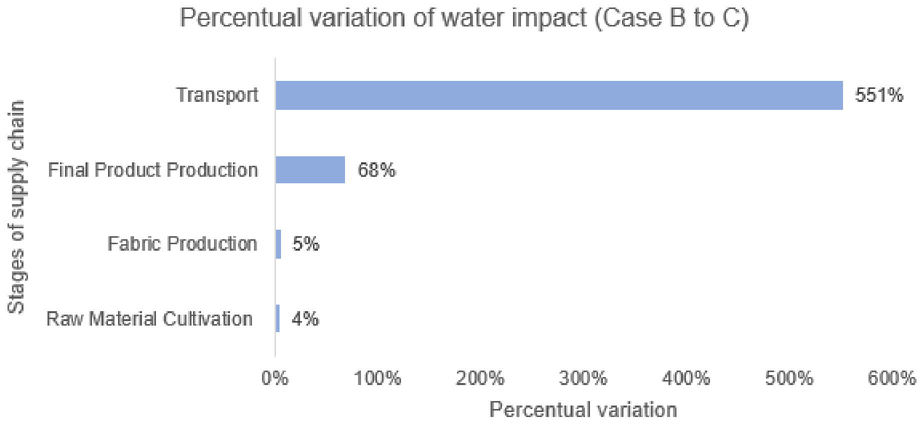


Figure 17: Percentual variation of water impact from case B to C.

Evidently, the additional 6.47E5 of water impact from case B to case C is predominantly owed to the decision, previously mentioned, of using truck for most of the flows. The same analysis was made, now for the percentual variation of the water consumption, represented in Figure 18.

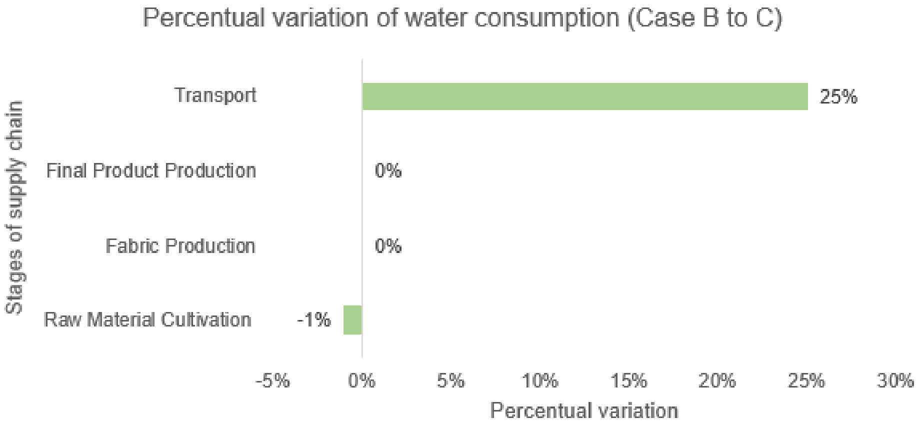


Figure 18: Percentual variation of water consumption from case B to C.

Once again, this additional analysis, along with the water consumption results in Table 22, allows to deduce the influence of the water stress in the overall water impact. According to Figure 18, the water consumed in transportation activities increases by 25%, a considerably lower variation than the 551% observed in the water impact associated with transport in Figure 17. Furthermore, although the water impact increases by 4% in the activities related to the cultivation and treatment of raw materials, there is in fact less water consumed in this stage in case C than in case B. It is also interesting to note that, although the water consumed in the fabric production is equal is both cases, as it should since the total production is the same, Figure 17 displays a variation of 5% in the water impact, from case B to C. This can be attributed to the water stress level of the regions where the production occurs. However, as it was mentioned before, there is no alteration in the mills leased from one case to the other. The aspects that do change are the production levels in the leased mills. In case C, the mill in Vietnam (M10) displays a higher production level than in case B, while the mill in Bangladesh (M1) displays a lower production level. Seeing as Vietnam has a higher water stress level than Bangladesh, the fact that more production is being assigned to M10 means that more pressure is being placed on the country's freshwater resources, which translates into a larger water impact.

5.2.2 Sensitivity analysis

Before proceeding with further analysis, it is important to perform a sensitivity analysis on some parameters. To undergo this analysis, the chosen parameters are the ones that, given the nature of its estimation, have a high uncertainty associated, or the parameters that proved to the be critical in the decisions made in the three cases presented so far, namely the factories' capacities, the costs and the water parameters.

Factories' Capacities (to case A)

Although leasing a smaller or larger capacity in each factory would involve several other factors for the company to consider, it was deemed relevant to study the changes it could bring to the network design and other major decisions.

The capacities of the factories were varied by +5%, +10%, +15% and +20%. The results indicate that a variation of +5% is enough for the generation of stock to cease to occur thus, the leasing of a warehouse is no longer necessary. This variation also means that one of the leased factories (F3) is able to operate slightly under its full production capacity at the last year.

Only when there is a variation of 20% is there a significant alteration in the network design, comparatively to case A. With a capacity of more 20%, it is no longer the most profitable option to lease 4 factories. Instead, there is only the lease of 3 factories, in Bangladesh (F1), India (F3) and Pakistan (F4), the factory in Egypt (F2) no longer necessary. Regarding the mills, the mill in Pakistan (M7) is leased instead of the mill in Egypt (M3) and there is an extra supplier, in Sri Lanka (S7). With more 20% capacity on each factory, F3 is no longer working at 100% capacity in the last year but instead operates at 97%.

To increase the capacity used at each factory leased is a complex decision that should be carefully weighted. In this work, although the capacities considered were a product of some estimations, they represent an indicative and realistic value in the industry thus, given that there are only relevant changes in the supply chain's superstructure with a variation of 20%, this parameter did not merit a major concern regarding the robustness of the model. However, if it is in the interest of the company to further research the capacities being leased, it should be highlighted that an increase lower than 20% does not seem to substantially disrupt the current network design.

Costs (to case A)

Every cost in the cost structure underwent a sensitivity analysis. Nonetheless, the study revealed that the network decisions did not alter themselves substantially or at all up until a variation of 100%, inclusive.

It is worth mentioning that an emphasis was put on the lease and hub costs, as their estimation had a higher degree of uncertainty than the remaining costs. For both, however, this uncertainty was not large enough to warrant realistic the increase of costs by a factor of two, when changes in the decisions began to occur. On the other end, a decrease of 20% was enough to alter part of the network design. This alteration is more noticeable with the variation of the lease costs, but it should be considered, for both parameters, that if an overestimation was made, the decisions in the network could be affected.

The most sensitive cost is the labor cost, which was expected since it represents a large portion of the cost structure. Having said that, the data related to the labor costs was considered well founded thus any deviations from the actual values would be too small to be highly significant.

Water (to case C)

The values regarding the water footprint of cotton were also put through a sensitivity analysis. It is extremely important, to ensure a robust model, to understand if a variation to these estimated values would significantly impact the decisions and the network obtained.

According to the results, the final decisions do not suffer any change when increasing these values by 100%, which assumes a largely pessimistic scenario where the considered data was significantly underestimated. On the other hand, when decreasing these values by 50%, which also corresponds to an implausible scenario, a few alterations were observed but they were considered negligible.

5.2.3 Multi-objective optimization

As observed, and as expected, the optimal solution for one objective function is not aligned with the others due to their conflicting nature. This creates a set of trade-offs that should be thoroughly explored and understood, to identify the solutions that best fit the specific problem at hand.

In this work, a lexicographic optimization and ε-constraint method were employed, as previously described in Section 3.3. To begin, the lexicographic method is employed and then the ε-constraint method delivers the Pareto optimal solutions through the Pareto Front.

The Pareto Front was obtained for the combination of the economic and water objectives. These were the core of the analysis since the maximization of the former represents the company’s priority and the minimization of the latter, the primary focus of this work. The Pareto Front achieved is represented in Figure 19.

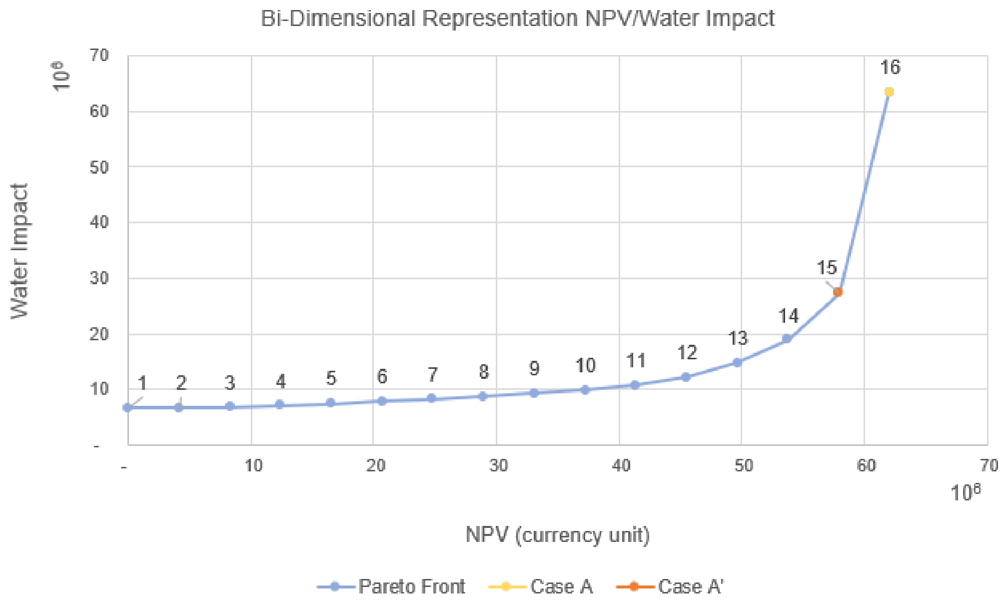


Figure 19: Multi-objective optimization: bi-dimensional representation of Water Impact against NPV.

Assuming as the extreme points for the NPV zero (case C) and 6.21E7, the optimum result for the economic function (case A), the line and the 16 points presented in the graphic translate the correspondent variations in the water function when varying the NPV. It is evident that only from the 15th to the 16th point is there a drastic change in the variation of the water impact, when compared to the previous points. Succinctly, this means that to increase the NPV by 7%, the supply chain increases his water impact by 57%, from a water consumption of 5.47×10^7 m^3 to 8.17×10^7 m^3 in case A. This is mainly due to decisions regarding the selection of suppliers. Table 23 below summarizes the results for each objective function for case A (16th point) and the 15th point, designated case A'. Note that the solution obtained for the jobs created also followed the same lexicographical method used previously.

Table 23: Single optimization results – case A and A'.

	NPV (c.u.)	**Water Impact**	**Jobs Created (per year)**
Case A	6.21×10^7	6.35×10^7	1.06×10^7
Case A'	5.80×10^7	2.73×10^7	1.57×10^7

Although the company is focused on its economic performance, these figures should be considered given that the water impact that derives from these scenarios can be crucial in the long-term water impact of the company's operations. In addition, the results also reveal that from case A to A' there is an increase of 48% in the quantity of jobs created per year, which is a substantial gain. The social enhancement will be further explained in Section 5.4.

5.3 Introduction of hemp raw material – obtained supply chain structure

The adoption of different raw materials, less water intensive than cotton, is a broad point of research within the apparel industry. The following section will focus on the impact that the introduction of a new product in the product-mix – FP2, jeans composed of cotton (RM1) and hemp (RM2) – could have in the supply chain's network design and in the decisions made.

5.3.1 Single objective optimization

Cases D and E

Two different single objective optimizations were analyzed for this new type of supply chain. Case D corresponds to the best performance for the economic objective function while case E delivers the optimum solution for the supply chain's water impact, assuming a non-negative cash-flow per year (similarly to case C). It is a more valuable analysis for the company to study the minimum water impact its supply chain can have without accepting a negative NPV, which would render the results impracticable. The results obtained for each objective function and for the water consumption in cases D and E are shown in Table 24.

Table 24: Single optimization results and water consumption – case D and E.

	NPV (c.u.)	**Water Impact**	**Water Consumption (m^3)**	**Jobs Created (per year)**
Case D	6.26×10^7	5.91×10^7	7.81×10^7	1.11×10^7
Case E	0	5.99×10^6	4.32×10^7	1.53×10^7

The network superstructure of case D is similar to the one of case A, with the exception of two new suppliers in China. As for case E, its network design also presents an extra supplier in India, comparatively to case C. Considering these additions, Figures 10 and 16, from subsection 5.2.1 can be consulted to better visualize the networks that will be now assessed.

From a brief and comparative overview of cases D and E, it can be stated that the number of entities composing each network is similar, with case E using an extra airport. Besides this, both networks make use of 7 suppliers, 3 mills, 4 factories and 1 warehouse. The main difference from one case to the other is the geographical position of the suppliers, the mills and the factories.

In case D, RM1 is sourced from the suppliers in Bangladesh (S2), Egypt (S5), India (S6) and the two in Pakistan (S8 and S9). The company also purchases RM2 from the two available suppliers in China (S3 and S4), which offer the cheapest price for raw material of any type. It is precisely due to the low prices S3 and S4 offer for RM2, that the decision to buy out all their available supply is made, which corresponds to a total of 200 ton of RM2. Since the next best prices practiced by the available suppliers belong to RM1, and the decisions are being driven by the NPV's maximization, the quantity purchased of RM2 remains the same throughout the entirety of the time span considered.

For case E, the suppliers in Austria (S1) and Bangladesh (S2) provide RM1 and RM2, the ones in Vietnam (S11 and S12) supply RM1 and the ones in China (S3 and S4) and India (S6) supply RM2. Although the water impact that derives from these choices is influenced both by the country's water stress level and its raw material's water footprint, it is worth noting that the five supplier countries with the lowest water stress level are in fact, in ascendent order, Austria, Bangladesh, Vietnam, China and India. On the other hand, for instance for RM1, China presents a less intensive water footprint than Vietnam, yet China is only chosen for the supply of RM2. While other factors could be influencing this choice, it could also be indicative that the water stress level index has a stronger influence on the supplier's selection than the raw material's water footprint.

The maps depicted in Figures 10 and 16 also indicate the location of the mills, factories and warehouses of each network. For case D, the mills leased are situated in Bangladesh (M1), Egypt (M3) and India (M4). One might reasonably infer that one of the main reasons to lease these mills is due to their proximity to the suppliers chosen, since all three mills are in the same country from where they receive their supply. However, for the suppliers in Pakistan, although the mills available in Pakistan are the closest, the costs of leasing a fourth mill did not justify the extra transport cost of moving the goods from S8 to M1 and from S9 to M4. In case E, the mills are located in Bangladesh (M1) and in Vietnam (M9 and M10), also the same country as part of their suppliers.

Both networks lease one warehouse in Pakistan (W5), only necessary in 2026 (the fourth year).

In both cases, most of the flows are done through road transport. Air transport is also used, in both cases to allow the delivery of final product to the clients in islands. Whereas in case D there is no flexibility to use a different (more costly), mode of transportation without it being strictly necessary, as it is for the islands, in case E, the plane is also used in the process of getting the raw material purchased in S1, into M1.

Production and Product-Mix

To acquire a deeper insight about the production decisions made, Figures 20 and 21 can be consulted as they translate the production levels of each final product in each year, for case D and E, respectively.

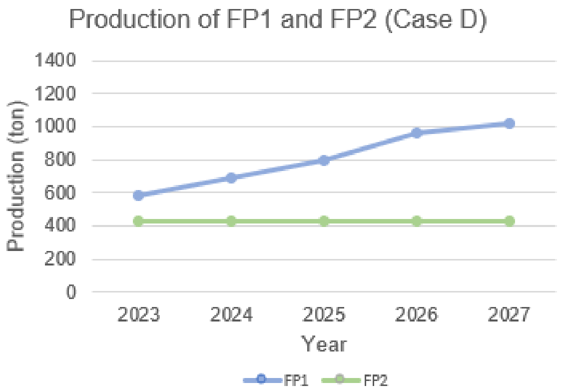


Figure 20: Factories' production levels – case D.

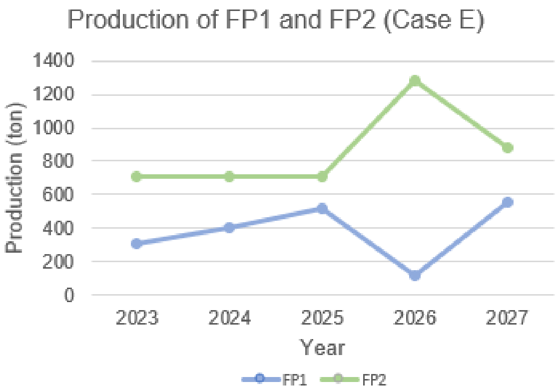


Figure 21: Factories' production levels – case E.

As it was mentioned before, in case D, the quantity of RM2 purchased is always the same. For this reason, the production level for FP2 is constant too, corresponding to 430 ton. Producing more than this would require purchasing more RM2 from a new supplier, which did not reveal itself as the best option from an economic perspective. The price of RM1 was lower than any other price practiced by the remaining RM2's suppliers. The production of FP1, as seen in Figure 20, increases steadily until the third year. On the fourth year, because part of the production of FP2 is stored as inventory, there is a higher increase in the production level of FP1, in order to meet demand. Consequently, on the last year, because the company makes use of that inventory, the production of FP1 does not increase as much as in the previous years. It should be remarked that if the present study was extended for more years, it is most likely that the produced stock would not be fully used to fulfil the demand in 2027. Not only this, but more stock could have been produced. However, given that the analysis only goes up until 2027, the best decision, both for economical purposes and for the overall water impact, is to use up all the stock available.

In case E, visible in Figure 21, the first three years follow the same pattern of case D, now with a higher production of FP2 and a lower production of FP1, which will be further discussed in the product-mix analysis. On the fourth year, again because of the creation of stock, there is a significant increase in the production level of FP2, coincident with a decrease in the production of FP1. The analysis of the water impact and the cost structure, that will follow, will be beneficial to better grasp the reason for this steep variation.

The product-mix of final product for case D and E can be seen in Figure 22.

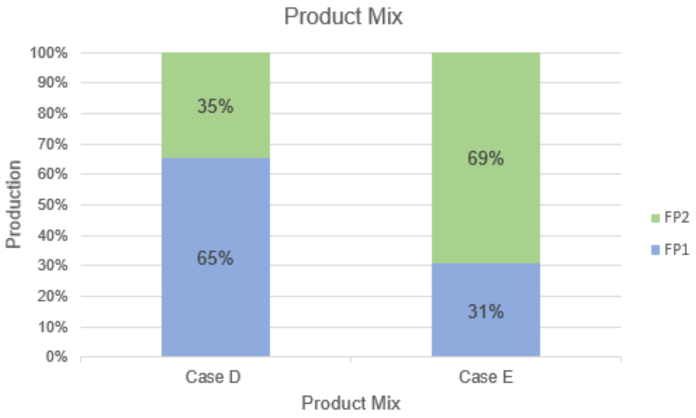


Figure 22: Product-mix – cases D and E.

The increase in the production of FP2, and consequent decrease in FP1 production, from case D to E was expected as it is aligned with the difference in each case's optimization goal. Since RM2 is a less water intensive crop, to increase FP2 production would most likely have a positive influence on the minimization of the water impact in the supply chain. This proved to be accurate as FP2 represents only 35% of the product-mix in case D but it almost doubles, to 69% in case E.

Water Impact

The results of the water impact, as previously shown in Table 24, are remarkably different between the two cases. Moreover, the water impact for case D of 5.91x10^{7} has an associated water consumption of 7.81x10^{7} m^{3}, while the water consumed in case E only reaches a total of 4.32x10^{7} m^{3}, which corresponds to a decrease of 45%.

The water impact that stems from the cultivation and treatment of the raw materials for each case is depicted in Figure 23.

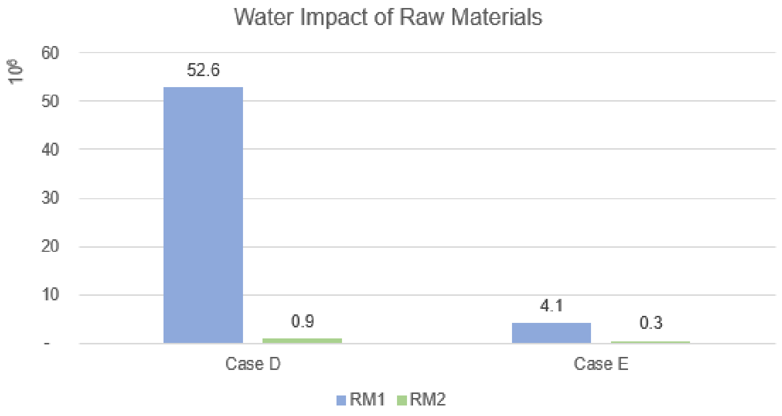


Figure 23: Water impact of raw materials – cases D and E.

According to the figure, while knowing that the production of FP2 represents more than half of the product-mix in case E, it is firmly established that the total water impact of obtaining RM2's is significantly lower than of obtaining RM1, highlighting just how large the difference between both raw materials' water requirements is.

Figures 24 and 25 display the water impact and consumption distribution, respectively, for cases D and E.

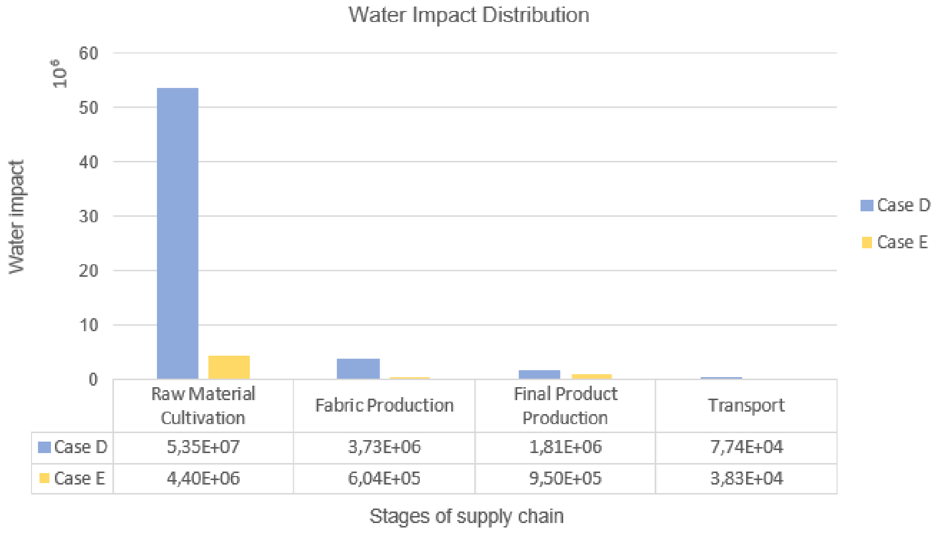
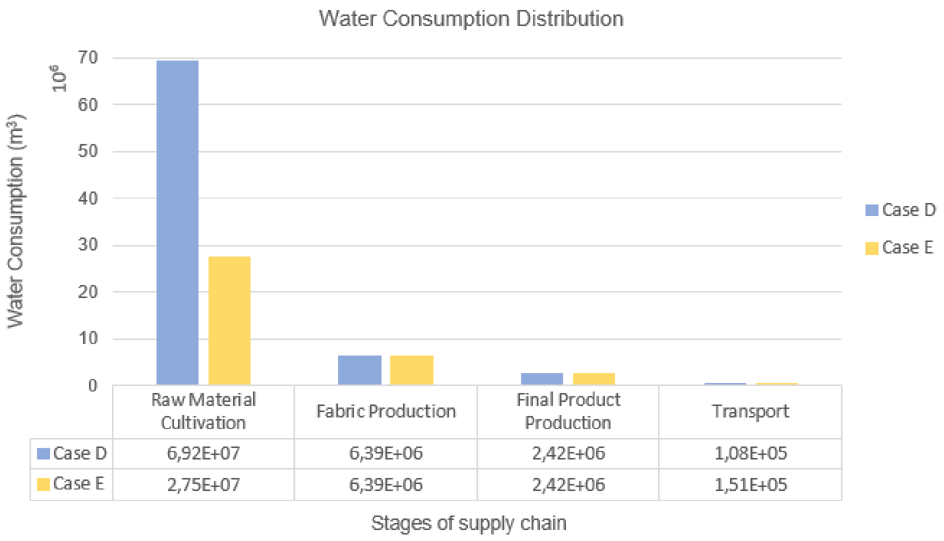


Figure 24: Water impact distribution – cases D and E.



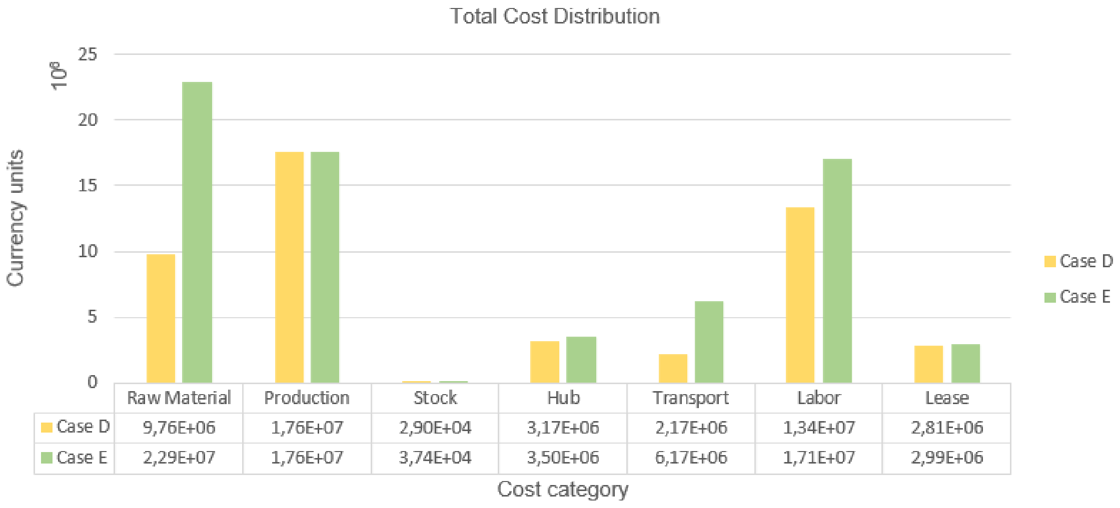
	Raw Material Cultivation	Fabric Production	Final Product Production	Transport
Case D	6,92E+07	6,39E+06	2,42E+06	1,08E+05
Case E	2,75E+07	6,39E+06	2,42E+06	1,51E+05

Figure 25: Water consumption distribution – cases D and E.

Similar conclusions as the ones obtained from the water analysis conducted in cases A and B, can be drawn from these two figures. The raw material cultivation still concentrates the largest amount of both water impact and water consumption, and the transportation activities the least. Furthermore, it is evidenced, once again, just how much influence the water stress level has on the water impact of the supply chain. It is clear, from the analysis of both figures, that a considerable improvement in the water impact of the production operations can be achieved simply by considering the water stress level of the regions where the production facilities are located. Not only this, but also the production's distribution between the leased facilities also influences the overall water impact.

Costs

The cost structure's distribution for both case D and case E can be consulted in Figure 26.



	Raw Material	Production	Stock	Hub	Transport	Labor	Lease
Case D	9,76E+06	1,76E+07	2,90E+04	3,17E+06	2,17E+06	1,34E+07	2,81E+06
Case E	2,29E+07	1,76E+07	3,74E+04	3,50E+06	6,17E+06	1,71E+07	2,99E+06

Figure 26: Total cost distribution – cases D and E.

As expected, apart from the production costs that are equal in both cases, as the total production requirements are the same, case D displays lower figures for every cost analyzed. Additionally, a major difference between the cases is in the raw material and transport costs, both of which more than double from case D to case E, the former increasing by 134% and the latter by 185%. Increasing the production of FP2 to reduce the overall water impact in the supply chain, drives the raw material costs up since RM2 is the most expensive raw material in almost every supplier. The only exception is China (S3 and S4), as mentioned before. This difference is also because, to produce FP2, there is a need for both RM1 and RM2. For this reason, it is also understandable that the transport costs are significantly higher in case E given that to produce the same quantity of final product, FP1 requires a single inflow of RM1 but FP2 requires both RM1 and RM2, which entails two different flows.

For case E, a more in-depth analysis of the variations between year 2025 (third year) and 2026 (fourth year) was carried out. The findings are summarized in Table 25.

Table 25: Costs' comparison between 2025 and 2026.

	Year		**Variation (%)**
Cost (c.u.)	2025	2026	
Raw material	4 486 919	4 685 237	+4
Production	3 488 825	3 972 028	+14
Stock	0	37 402	-
Hub	700 762	700 762	0
Transport	1 229 976	1 206 308	-2
Labor	3 422 434	4 120 879	+20
Lease	598 984	598 984	0

As referenced before, the creation of stock in the fourth year implies an additional cost to account for, the stock cost of 37 402 c.u.. This new cost, alongside the forecasted increase in the demand, which increases the raw material, production and labor costs, requires an adjustment in the decisions made. It is necessary to counteract these augmentations to continue to deliver a non-negative cash-flow per year. The balance is reached through the decrease in the transport costs (-2%) in the network's flows of raw material. The longest path taken from a supplier to a mill is the one between S1 and M1. To reach M1, the raw material is first transported by truck to the airport in Egypt (A5), then flown to the airport in Bangladesh (A2) where it is finally driven by truck to M1, travelling a total of 8 167 km. Although S1 supplies both RM1 and RM2, only the flow of RM1 was reduced to offset the new costs, since the optimization goal of case E is to minimize water impact. For this reason, the production of FP2 is prioritized over the production of FP1.

5.3.2 Sensitivity analysis

A sensitivity analysis was also performed to this supply chain, however, it solely focused on the water footprint of the raw material hemp. The analysis of this parameter, similarly to the cotton's water footprint, was deemed important given the weight it has over the water impact of the supply chain. In addition, this parameter was obtained through some estimations, as explained in Chapter 4, thus it is relevant to assess its robustness. The sensitivity analysis was performed under the same conditions as case E.

Assuming an underestimation of the water footprint values considered, it was concluded that only from a 20% variation up were there meaningful changes in the suppliers' selection. The suppliers of RM2 required decreases as the variation of hemp's water footprint increases. A +20% variation does not make use of one of the suppliers in China, whereas a variation of 30%, 40% and 50% does not require either of the suppliers in China. Given that only the water impact of producing FP2 is increased, a more efficient solution, water wise, is to decrease its production. Alterations in the remaining decisions were deemed irrelevant. It was also concluded that, in the case of an overestimation of 20%, the network design does not suffer any changes, but there is only the production of FP2.

The sensitivity analysis' findings emphasize the importance of using the most precise water footprint value for a raw material when appraising its water impact on the supply chain. For this study, the data used was assumed to be accurate enough that a 20% deviation in the values would not be unreasonable, but an improbable scenario.

5.3.3 Comparison between supply chains and multi-objective optimization

Before delving into the multi-objective optimization of this new supply chain, it is important to carry out a comparative overview between the two types of supply chain, in order to display their main differences.

In regard to their networks' designs, as it was mentioned before, there is only a significant difference in the suppliers chosen. With the introduction of hemp, for both cases D and E, the supply chains obtained required additional suppliers, when compared to cases A and C, respectively. In addition, besides the expected changes in the production decisions, already detailed, the inventory decisions also vary. Moreover, in the supply chain that incorporates hemp, the inventory created consists of FP2, instead of FP1. Finally, as for the water impact calculated, Table 26 showcases the findings concerning the variation of the water impact per stage of the supply chain between case A and D and case C and E, respectively.

Table 26: Water impact variation between cases A and D and cases C and E.

	Raw material cultivation	**Fabric production**	**Final product production**	**Transport**
Variation (A - D)	-8%	0%	0%	-3%
Variation (C - E)	-13%	0%	-1%	-2%

According to the results, the reduction in the water impact is primarily due to the raw material's agricultural requirements. However, some benefits stem also from the production of final product and from the transportation network adopted.

In the same manner as in subsection 5.2.3, the next phase of the analysis consists in exploring the potential feasible solutions derived from the optimization of both the economical and water impact objective functions.

To accomplish that, a new Pareto Front was generated, illustrated in Figure 27, now considering the new type of supply chain in which there is the usage of hemp as a raw material. It was calculated based on the solutions obtained for case D and E, which correspond to the extreme points of the graph. Besides the Pareto Front, Figure 27 also shows the Pareto Front previously obtained between case C and A.

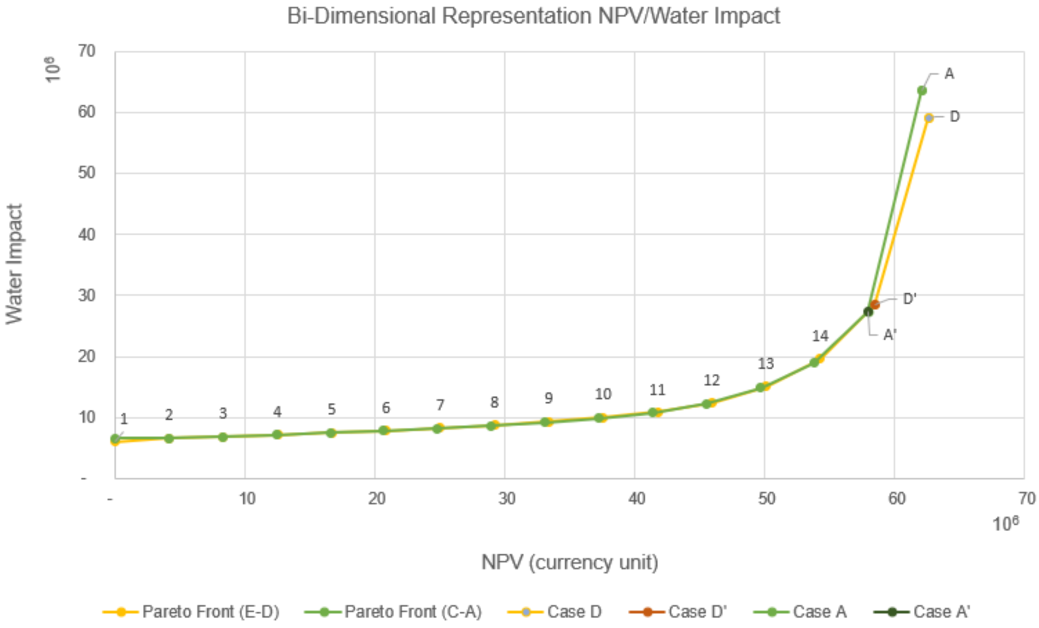


Figure 27: Multi-objective optimization: bi-dimensional representation of Water Impact against NPV (comparison between Pareto Front (C-A) and Pareto Front (E-D)).

It is clearly visible in the graph that case D yields higher results for the economic performance and lower results for the supply chain's water impact than case A. In fact, as it will be further detailed in the following subsections, case D showcases an improvement from case A in all three objective functions and in the environmental impact, also considered. These results are summarized in Table 27.

Table 27: Single optimization results and variation – case A and D.

	NPV (c.u.)	**Water Impact**	**Jobs Created (per year)**	**Environmental Impact**
Case A	$6.21\text{x}10^7$	$6.35\text{x}10^7$	$1.02\text{x}10^7$	$2.19\text{x}10^6$
Case D	$6.26\text{x}10^7$	$5.91\text{x}10^7$	$1.11\text{x}10^7$	$2.13\text{x}10^6$
Variation	1%	-7%	5%	-3%

A reduction of 7% in the water impact is a significant gain, even more so given that it also improves the company's economic performance, increases the number of jobs created and it reduces the environmental impact of the supply chain. Nonetheless, due to the significant variation between the 15th (identified in Figure 27 as case D') and 16th point of the Pareto Front, a more thorough analysis was made to this potential solution.

Table 28 presents the values obtained for case D’.

Table 28: Single optimization results – case D’.

	NPV (c.u.)	Water Impact	Jobs Created (per year)
Case D’	5.84×10^7	2.84×10^7	1.58×10^8

It was found that the water impact of the supply chain decreases by 52%, which corresponds to a water consumption variation of 55%, going from 7.81×10^7 m^3 in case D to 5.03×10^7 m^3 in case D’. Moreover, the jobs created experience a drastic increase from case D to case D’, by 1318%. Conversely, the NPV obtained at the end of the 5 years is 7% lower in case D’, creating a complex trade-off that delivers a worse economic performance.

The comparison between case D’ and case A’ was also made and it can be visualized in Figure 27 as well. Although very similar, it shows that case D’ delivers a better result for the economical function (+1%) but a worse result for the water impact (+4%) function than case A’. However, as it will be further detailed in the following subsections, case D’ also achieves better outcomes that case A’ in the social and environmental dimensions.

5.4 Social objective function

The social dimension was translated into an objective function that accounts for the number of jobs created within the supply chain per year. The indicator used encompasses the jobs created in mills, factories, warehouses and within the transportation sector. To truly have a holistic view of the supply chain’s impact, assessing the social impact, at least to some degree, is fundamental. Table 29 summarizes all the social results of the previous analyzed cases.

Table 29: Social results of all cases analyzed.

	Jobs Created (per year)
Case A	1.06×10^7
Case B	8.65×10^7
Case C	1.73×10^7
Case D	1.11×10^7
Case E	1.53×10^7
Case A’	1.57×10^7
Case D’	1.58×10^8

Following the comparative path taken throughout Chapter 5, some conclusions can be drawn.

Firstly, the variations observed between the quantity of jobs created directly derive from the jobs created in the transportation and inventory management sectors. The quantity of jobs generated to meet production needs is constant for all cases analyzed, given that the demand for final product is identical in all of them.

The noticeable difference between the quantity of jobs created per year between case A, when the NPV is being maximized, and case B, when the water impact is being minimized, is primarily due to the difference in the jobs created in the transportation sector. In case B, the preference for transport by sea and railway, both of which require a significant larger quantity of workers than truck and plane, increases the number of jobs considerably. That being said, the increase in inventory production also requires a larger workforce in the warehouse.

The social performance of case C, as expected, falls between case A and case B's results, as the costs of using the less water intensive transports are too high. Having more flows transported by truck leads to fewer flows overall, since there is no need to move the goods to a transportation infrastructure, consequently reducing the number of jobs created.

With the introduction of hemp as a raw material, as detailed previously, the social impact of the supply chain is improved by 5%, going from $1.06\text{x}10^7$ jobs in case A to $1.11\text{x}10^7$ jobs in case D.

Presented in Table 29 as well, are cases A' and D'. Case A' exhibits an improvement in the social dimension, comparatively to case A. Case D' presents the highest result achieved in the social function for any of the cases analyzed, and 1318% higher than in case D. This is directly related to the fact that case D' presents the highest quantity of flows, highest number of suppliers used in the network and, finally, it makes use of all types of transport modes available, which only transpired in one other case, case B.

5.5 Environmental impact

An environmental analysis was conducted as well, in order to understand if focusing only on water optimization could have a negative impact in other environmental impact categories. Figure 28 presents the results obtained for the total normalized environmental impact for each case analyzed. The columns in blue represent the scenarios in which the supply chain exclusively traded FP1 and in green the cases where there were both FP1 and FP2 as final products.

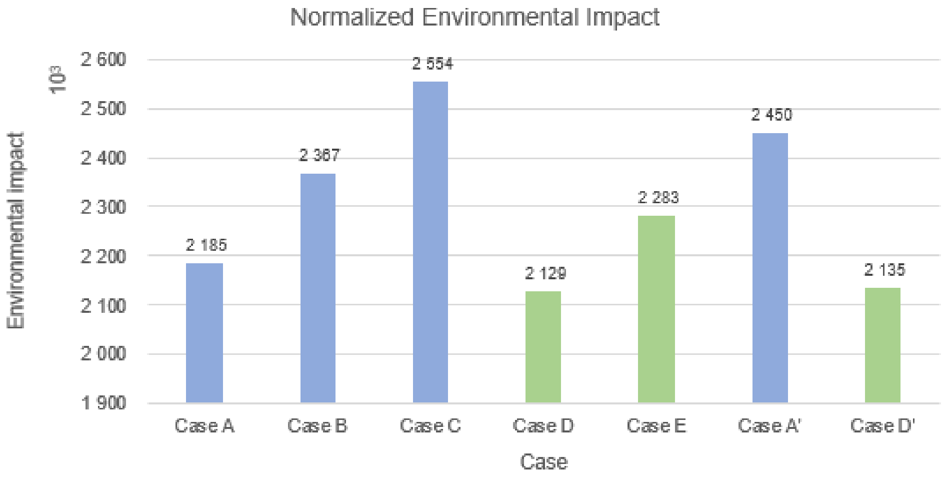


Figure 28: Environmental impact results of all cases analyzed.

According to the values obtained, one can infer that the environmental impact is the lowest when the economic function is being optimized (cases A and D). The results for cases B, C and E, all of which minimize the water impact, are higher than the ones of case A and D. This is primarily due to the increase in the quantity of flows and, consequently, the increase in transport, from the NPV's optimization to the water impact optimization.

When comparing between the blue and green columns, case D yields a lower result than case A and case E a lower result than case C. Although the differences are extremely small, the results indicate that a supply chain that trades both FP1 and FP2 has less of an environmental impact than a supply chain that only exchanges FP1. It is also worth mentioning that, although case D' has the highest quantity of flows and uses all types of transport modes available, its environmental impact is still one of the lowest out of all cases analyzed, specifically, when compared to case A'.

A closer look was taken to the environmental impact in each midpoint category. Figure 29 illustrates the sum of the impacts obtained for each product in the supply chain for cases A and B, which use equal quantities of RM1 and have the same production, thus the same environmental impact for the production activities.

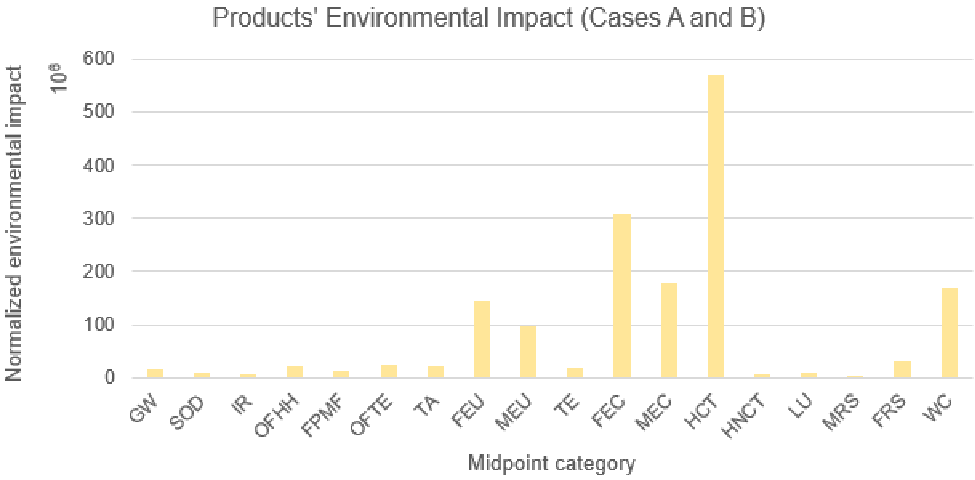


Figure 29: Products' environmental impact per midpoint category – cases A and B.

The raw material cultivation and the production of fabric and final product made of 100% cotton, have a critical impact on the category human carcinogenic toxicity (HCT) and freshwater ecotoxicity (FEC). HCT's indicator is the risk increase of cancer disease incidents and it includes all chemicals with reported carcinogenic effects. FEC's indicator is the hazard-weighted increase in freshwaters (National Institute for Public Health and the Environment, 2017). Like for many other crops, cotton's cultivation has become highly dependent on the use of agrochemicals (fertilizers, herbicides and pesticides). The excessive use of agrochemicals has a large impact on human health, from both direct and indirect contact with the substances, and on surface and ground water contamination (Kannuri and Jadhav, 2018).

The previous analysis was also conducted for case D and case E. It was found that the incorporation of hemp, despite reducing the values obtained for the total products' environmental impact, does not substantially change their order from most to least impactful. The single difference in the order concerns the midpoint categories freshwater eutrophication (FEU) and water consumption (WC). While in cases A and B, WC is the fourth and FEU the fifth most impactful, in cases D and E, it is the opposite. FEU's indicator is the phosphorus increase in freshwater and WC's the water consumed, in m^3, (National Institute for Public Health and the Environment, 2017). While it is not the indicator chosen to evaluate the water impact for the present work, as justified in Chapter 4, it should be highlighted that the ReCiPe 2016's indicator of water consumption delivers similar results as this work's – the production in a supply chain that includes hemp as a raw material consumes less water than a supply chain that only includes cotton.

Finally, a comparison was made, between case A and case D, for the distribution of environmental impact between the different stages of the supply chain. Figure 30 translates the results obtained.

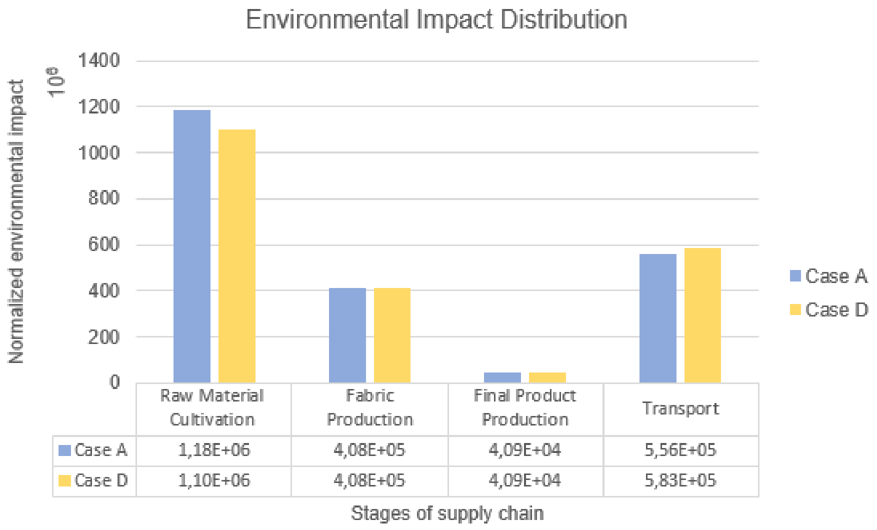


Figure 30: Environmental impact distribution – case A and case D.

As seen in Figure 28, case A presents larger environmental impacts than case D. Now, by analyzing Figure 30, it can be inferred that this reduction comes from the raw material cultivation stage in the supply chain. The transportation activities are the second most impactful segment in the supply chain, and case D delivers higher results than case A. This is primarily due to case D presenting more flows than case A, as one could expect. However, these transport impact in case D are still not large enough to warrant it a worse environmental outcome than case A.

5.6 Stochastic demand analysis

The analyses conducted thus far assumed a deterministic demand, which increases by 10% every year. Nevertheless, forecasting demand is a complex task with a great deal of inherent uncertainty. For this reason, it is important to consider the variability in the demand in order to improve the company's planning for different contingencies. To do this, a stochastic approach was taken, through the implementation of scenarios in the mathematical model, as described in Chapter 4, section 4.2.

The following scenarios were studied for this analysis:

- The base scenario, with the original expected demand and a probability of 50%.
- Scenario 1, with an annual demand growth of 5% and a probability of 25%.
- Scenario 2, with an annual demand growth of 20% and a probability of 25%.

The model was then optimized towards the maximization of the economical function, as in case D. The results from both case D, which considered a deterministic demand, and case D1, where a stochastic demand was applied, can be consulted in Table 30.

Table 30: Entities, costs and objective function's results for deterministic (D) and stochastic demand (D1).

	Cases	
	Case D	**Case D1**
Contracted suppliers	7	8
Leased mills	3	3
Leased factories	4	5
Leased warehouses	1	1
Raw material costs (c.u.)	9.76×10^6	1.01×10^7
Production costs (c.u.)	1.76×10^7	1.81×10^7
Stock costs (c.u.)	2.90×10^4	1.56×10^5
Hub costs (c.u.)	3.17×10^6	3.17×10^6
Transport costs (c.u.)	2.17×10^6	2.37×10^6
Labor costs (c.u.)	1.34×10^7	1.62×10^7
Lease costs (c.u.)	2.81×10^6	3.17×10^6
NPV (c.u.)	6.26×10^7	5.81×10^7
Water impact	5.91×10^7	6.03×10^7
Social benefit (jobs created per year)	1.11×10^7	1.22×10^7

According to the results, if the company opts to rely in a stochastic demand approach, it will require two additional entities in its network, one supplier and one factory, comparatively to case D.

Overall, the inclusion of uncertainty in the demand, causes the supply chain's costs to slightly increase, which leads to a reduction of 7% in the NPV, comparatively to a deterministic demand. Nonetheless, both scenarios display a profitable supply chain. Case D1 also displays a negative variation for the water impact function, which is 2% higher when employing a stochastic approach. Finally, the social benefit is the only result that showcases an improvement, with an increase of 10% in the number of jobs created.

Given the somewhat significant alterations observed between case D and case D1, it is worthwhile for the company to include some uncertainty in its demand forecasting methods, as it will provide it with a higher level of support in its long-term decisions.

5.7 Recommendations

Following the comprehensive analysis of the results, the next step entails advancing to the recommendations developed.

Should the company intend to maintain its current line of products, represented by FP1, the findings obtained indicate that there are strategies that can be taken to minimize the supply chain's water impact. First and foremost, it should be highlighted that simply acquiring an understanding of the water impact associated with the supply chain, is already an important step and improvement for the company.

Considering the available entities the company has at its disposal, the highest achievable NPV, at the end of the 5 years, is of 6.21x10^7 c.u., which corresponds to a water consumption of 8.17x10^7 m^3 and a water impact of 6.35x10^7 (case A).

However, according to the results, **it was established that if the company is open to a slight adjustment in its priorities, a significant improvement can be made in its water impact, which can decrease by 57%, to 2.73x10^7. This value represents a water consumption of 5.47x10^7 m^3. Case A' translates this improvement, at the cost of decreasing the company's NPV by 7%, to 5.79x10^7 c.u.. In counterpart, the number of annual jobs created also increases, by 48%, which provides an annual income to more 5.11x10^6 people. As for network structure's alterations, the only difference from case A concerns the suppliers' locations.** Given this information, the company could also use the values for the water impact improvement as a reference and invest in projects that enhance water efficiency at the existing suppliers in case A. However, the water stress should still be acknowledged since it is crucial to allow for the regeneration of the freshwater resources of the suppliers' locations. This option, which highlights a significant trade-off, merits further examination by the company's decision makers. It is advised that, should the economic toll of 7% be considered too high, the company should establish a threshold for the maximum sustainable NPV loss it would be willing to undertake, given that, according to the multi-objective optimization of subsection 5.2.3, from the best economical outcome (case A) to the presently recommended scenario (case A'), it is expected that just a small decrease in the NPV will be counteracted with a significant decrease in the water impact.

Regarding the company's interest in potentially incorporating hemp as a raw material and, consequently, a new type of final product into its product-mix (FP2), the results obtained (case D) suggest that it would be a rewarding alternative to trading only FP1, on all counts. From a water impact perspective, the company would yield a lower result, reducing its impact by 7%, which corresponds to less 3.60x10^6 m^3 of consumed water. From an economic perspective, it would also result in a more profitable supply chain, increasing its NPV by 1% (5.36x10^5 c.u. more). The social and environmental benefits would increase as well, by 5% and 3% respectively.

Finally, in case the company is truly committed to introducing hemp in its supply chain, a further step could be taken to achieve an even better outcome in terms of the company's water impact. By adopting the network structure and the decisions made in case D' the company would be reaching one of the possible compromises alluded to when discussing case A', that slightly lessened the trade-off between economic and water impact performance. This way, the company could still significantly reduce its water impact to 2.84x10^7, and its water consumption to 5.03x10^7 m^3, but its NPV would only be reduced to 5.84x10^7 c.u..

The main decisions of each of the cases mentioned in this recommendation section can be better compared by analyzing Table 31.

Table 31: Main decisions' results summary for case A, A', D and D'.

	Cases			
	Case A	**Case A'**	**Case D**	**Case D'**
Suppliers of RM1	S2, S5, S6, S8 and S9	S2, S5, S6, S10, S11 and S12	S2, S5, S6, S8 and S9	S2, S5, S6, S7, S8, S11 and S12
Suppliers of RM2	-	-	S3 and S4	S3 and S4
Mills	M1, M3 and M4	M1, M3 and M4	M1, M3 and M4	M1, M3 and M7
Factories	F1, F2, F3 and F4			
Warehouses	W5			
Product-mix	100% FP1	100% FP1	65% FP1, 35% FP2	65% FP1, 35% FP2
Transportation	Mostly road transportation is used. Air transportation is used to supply all clients in islands.	Mostly road transportation is used. Air transportation is used to supply all clients in islands.	Mostly road transportation is used. Air transportation is used to supply all clients in islands.	All transportation modes are used. Air transportation is only used to supply two clients in islands.
NPV (c.u.)	6.21×10^7	5.79×10^7	6.26×10^7	5.84×10^7
Water impact	6.35×10^7	2.73×10^7	5.91×10^7	2.84×10^7
Social benefit (jobs created per year)	1.06×10^7	1.57×10^7	1.11×10^7	1.58×10^8
Environmental impact	2.19×10^6	2.45×10^6	2.13×10^6	2.14×10^6

6 – Conclusion

The concluding chapter is divided in two sections. Section 6.1 summarizes the principal conclusions of the work carried out in this dissertation while Section 6.2 addresses the limitations of the study as well as recommendations for future work.

6.1 Conclusions

Driven by the urgent global water crisis and the consequent imperative need to address this issue in the planning of sustainable supply chains, the necessity to build on the field of sustainable water management strategies in supply chains is evident, as stressed by Cole et al., (2022).

As industries grapple with the pressing water crisis, which is expected to be exacerbated by the consumption's increase, particularly of the emerging Asian middle class, supply chains must acknowledge and combat the water impact of their entities and activities. This holds especially true for the textile and apparel industry, an industry heavily dependent on the Asian continent and its freshwater resources. Given the growing environmental concerns facing the sector, there has been a drive to explore new water management strategies, many of which related to the adoption of more sustainable fibers than cotton, such as hemp. According to existing literature, this raw material has been witnessing a resurgence and it shows immense potential in the textile industry.

The conducted literature review shed some light on the lack of mathematical models, within the textile industry, that optimize the design and planning of a sustainable supply chain, considering a triple bottom line approach. Additionally, the few researchers that contributed to this specific field, have rather overlooked the relevance of water-related impacts in the sector's supply chains.

This work contributes to this area of research by presenting a strategic decision support tool for the planning and design of a supply chain network, through a muti-objective MILP model, that optimizes three objective functions: economic, water impact and social. The model incorporates decisions related to suppliers' selection, production and storage facilities selection, transportation network, product-mix definition and production and inventory needs.

One of the main contributions of this work is related to the water impact objective. The concept of water footprint was adopted in this model, as encouraged by several experts on the matter, but the measurement of the supply chain's water impact relied on other indicators as well. The water footprint was used for the agricultural stage, where each raw material analyzed presented a different water footprint considering the supplier's location. For the remaining supply chain operations, the water consumption was accounted for as well. Finally, the water impact of the supply chain also accounted for the water stress level index of each region an entity used in the network design was located. This allowed for the decisions made, when optimizing the water impact, to not only consider the amount of water used but also the availability of freshwater resources in the regions where the raw materials and products were being retrieved from, produced in and transported from.

The model was implemented in a case study regarding an apparel company, optimizing the company's economic performance, overall water impact and the employment generation, as a social aspect. If properly adjusted, the tool can prove to be useful for many other industries that are planning the structuring or restructuring of their networks, while considering these three conflicting objectives.

Two research questions were posed and answered to in this work. The first intended to know how supply chains' network design can be adjusted to face the increasing depletion of freshwater resources and expected increase of its requirements and the second aimed to determine the impacts associated with the introduction of hemp as a textile raw material. Three cases were initially analyzed for the first question (cases A, B, and C), where the company only traded one type of final product (FP1); and two other cases were studied for the second question (cases D and E), where a new type of final product (FP2) was introduced in the product-mix, partly made with hemp (RM2). All of these cases were first analyzed through a single objective optimization approach, while implementing the lexicographic method. This allowed to obtain the best possible result for the second and for the third objective function, while maintaining the results already obtained from the previously optimized objective functions.

For the multiple-objective optimization problem, employing the lexicographic and the ε-constraint methods, made it possible to obtain valuable insights into the company's supply chain. The multiple objectives considered exposed the trade-offs amongst optimizing economic, water impact and social goals. Only by revealing and analyzing these conflictual interactions, can the decision-makers acquire the knowledge required to make balanced managerial decisions that will better enhance the interests of their companies. A larger focus was placed on the trade-offs obtained when attempting to optimize both the economic performance and the water impact objectives. It was concluded that the network design of a supply chain can in fact be adjusted in order to contribute less to the current depletion of freshwater resources. This can be achieved by analyzing the water impact a certain activity in the supply chain will have, by measuring the water consumed in that activity, on the available freshwater resources of the area it is done in, measured by the water stress level index. In the case study analyzed, it was possible to reduce the company's water impact by 57% while withstanding a much lower 7% reduction on the company's NPV. The introduction of hemp as a textile raw material, more specifically adopting a product-mix composed 35% of FP2, also proved to be a profitable decision and beneficial in terms of water impact. By adopting this raw material, the company's NPV increased by 1% (more 5.36×10^5 c.u.) and the company's water impact decreased by 7%, with a reduction of 3.60×10^6 m^3 of consumed water. The employment generated would also increase, by 5% and the overall environmental impact of the supply chain decreased by 3%. Thus, the potential of this raw material as an alternative raw material in the industry is well founded and, although it is still not the most profitable to undergo a complete substitution of cotton for hemp, the incorporation of the fiber in the production of new clothing is an investment more apparel companies should investigate.

Several sensitivity analyses were performed, focused on factories' capacities, cost and water parameters, which held substantial relevance in the decision-making process of the model. The analysis demonstrated the model's robustness, as the network and the decisions did not exhibit significant alterations to reasonable variations of these parameters. Nonetheless, it should once again be underscored the criticality of using the most accurate values available for these parameters.

A stochastic demand analysis was also conducted to deal with the inherent uncertainty of forecasting demand. Given that, when considering the probabilistic scenarios created, the analysis revealed slightly worse results for the economic and water performances, -7% and -2% respectively, it would be beneficial for the company to take into account a stochastic demand, as it will provide the company with a better preparation to face different contingencies.

6.2 Limitations and future research suggestions

As with any research, this study is subject to limitations. It is essential to acknowledge limitations, not only to promote transparency, but also to contribute to the advancement of knowledge.

A main limitation of this dissertation is associated with the data collected, necessary for the development of the case study that aimed to validate the constructed model. Given the estimates that had to be made, due to the shortage of publicly available information, introduces an element of uncertainty in the model's input values, thereby risking a certain degree of uncertainty in the obtained results. Parameters central to the cost structure of the company and the water parameters are of extreme importance. Ideally, these parameters should exhibit the least amount of uncertainty as possible, so that the model yields the most realistic results. Furthermore, the estimation of distances in the network has its own set of limitations, as it was based on the Euclidean distance formula that considers a straight-line distance between two points. This is not representative of the existing transport infrastructures or the impracticalities of having a flow going linearly from one point to the other, for instance geographic and topological conditions.

Future work can extend the current model by placing a larger focus on the social dimension and employing the ε-constraint method, and obtain the Pareto set of optimal solutions, between the economic and social objectives, as well as between the water and social objectives. This could offer a more holistic understanding of the supply chain. Additionally, other social indicators can be used to measure the social impact of the supply chain. For example, (Mota et al., 2018) designed a social indicator that gives preference to the supply chain entities that are located in regions with lower gross domestic product (GDP). Another direction for the social dimension can be taken based on the research conducted by Messmann et al. (2023), which studied a comprehensive set of applicable quantitative social indicators, such as fair salary and local employment, among others. The environmental assessment could be included as an objective function as well and optimized simultaneously with the other three objective functions, according to different indicators, for instance the minimization of carbon emissions.

Given the expected persistence of purchasing powers' discrepancy of the global middle class, new models should be developed to help companies enter the Asian market and provide products that cater to multiple preferences and price points, while still considering the economic, environmental and social aspects of the supply chain.

Lastly, it is encouraged that other potential textile fibers, besides hemp, are investigated further as alternatives for cotton, a very water-dependent crop. La Rosa and Grammatikos (2019) have contributed to this research and have also highlighted jute and kenaf as less water-intensive crops, when compared to cotton. By employing the model developed in this work, it would be possible to further evaluate the economic, water and social impacts of incorporating these other raw materials in a supply chain.

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Appendix

Table 32: Units and normalization factors of midpoint categories.

Midpoint Category	Unit	Normalization Factor
Global warming	kg CO2 eq	0,000125
Stratospheric ozone depletion	kg CFC11 eq	16,7
Ionizing radiation	kBq Co-60 eq	0,00208
Ozone formation, Human health	kg NOx eq	0,0486
Fine particulate matter formation	kg PM2.5 eq	0,0391
Ozone formation, Terrestrial ecosystems	kg NOx eq	0,0563
Terrestrial acidification	kg SO2 eq	0,0244
Freshwater eutrophication	kg P eq	1,54
Marine eutrophication	kg N eq	0,217
Terrestrial ecotoxicity	kg 1,4-DCB	6,58E-05
Freshwater ecotoxicity	kg 1,4-DCB	0,0397
Marine ecotoxicity	kg 1,4-DCB	0,023
Human carcinogenic toxicity	kg 1,4-DCB	0,0971
Human non-carcinogenic toxicity	kg 1,4-DCB	3,20E-05
Land use	m2a crop eq	0,000162
Mineral resource scarcity	kg Cu eq	8,33E-06
Fossil resource scarcity	kg oil eq	0,00102
Water consumption	m3	0,00375