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

Martina Lourenço Monteiro

Industrial Engineering and Management, Instituto Superior Técnico

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 $5.36\text{x}10^5$ currency units, the water consumption by $3.60\text{x}10^6$ 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

1. Introduction

Over the past few decades, the world has been stage to an increasing over-exploitation of freshwater resources. The witnessed population growth and the economic move towards a more resource-intensive pattern of consumption have risen global water withdrawals by almost 600% since 1900 (Hannah Ritchie and Max Roser, 2017).

Multiple reports express a rapid expansion of the "global middle class", with some projections estimating that it will more than double from 1.8 billion to 5 billion, from 2009 to 2030 (ESPAS, 2015). The consumption of the emerging middle classes will be marked by a higher demand for diversified products, and it is 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). These projections place substantial momentum in Asia, prompting companies to position their businesses closer to these customers. Thus, 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. By 2030, it is expected that China and India will assume a leading position, 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. (World Bank, 2018).

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). The sector has Asia as its production and exports epicenter and the industry is one of the largest consumers of freshwater, consuming approximately 79 billion m^3 of freshwater per year (Environmental Audit Committee, 2019). To address environmental concerns, the shift towards more sustainable fibers has been growing in the textile and apparel industry with the raw material hemp being praised for his sustainability potential in the textile industry.

The rise of the middle class will instigate a rise in various products' demand, namely apparel. This will lead to an increase in production, increasing the need for freshwater resources. Furthermore, the concentration of production in Asia, which is expected to house a large 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 extremely important to design and plan textile supply chains that consider the water implications of its network.

The objective of the present work is to contribute to the body of research concerning the design and planning of 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, supporting 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?

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

Through the development of a MILP optimization model, applied to a case study of an apparel company, it is expected that valuable managerial insights can be offered to decision-makers related to decisions that concern supply chain's entities' selection as well as production, inventory and transportation necessities. The model includes the triple bottom line approach by considering the economic, environmental and social dimensions.

2. Literature Review

Recognizing the textile sector's substantial contribution to global water scarcity, researchers worldwide have addressed this topic to seek solutions to promote sustainable water management practices in the industry.

As Li et al. (2021) have pointed out, an important step in overcoming this problem is evaluating water consumption and wastewater production. The authors also highlight the value of employing methods such as the Water Footprint Assessment (WFA) to obtain these values. The water footprint (WF) measures the total volume of freshwater used, directly and indirectly, in the production of a consumed good or service and several studies, such as the one by Morgan et al. (2022), have revealed that a significant portion of water consumption in the textile industry is linked to fiber production.

There is an extensive body of literature that highlights hemp (Cannabis sativa L.) for its versatility and its significant potential within the textile and apparel sector, as a fiber. Per Andre et al. (2016), hemp's resurgence is partly due to its agricultural features such as resistance to drought, pests and soil erosion, as well as its low water needs compared to other crops, like cotton. Zimniewska (2022) discusses approaches to hemp fiber extraction and notes that the bottleneck of the hemp textile value chain is the spinning system due to a lack of specialized equipment. The author concludes that the most feasible direction for developing hemp yarn is by adapting cotton spinning systems for cottonized hemp fibers, which blends hemp with cotton or similar fibers. Duque Schumacher et al. (2020) focused on examining hemp from an economic and environmental standpoint. The authors conclude that hemp is economically competitive and a feasible sustainable alternative to cotton. Kaur and Kander (2023) also reviewed hemp's sustainability across economic, environmental and social dimensions. They note, however, that the hemp supply chain still faces several economic uncertainties, and the commodity should be approached with caution. Regarding the social dimension, the authors express that hemp's ability to establish local and regional supply chains is linked to its social value as a raw material but conclude stating that additional research is needed to quantify the social sustainability of industrial hemp.

Addressing supply chain design and planning involves complex and strategic decision-making, particularly with the growing pressure companies have been under to adopt sustainable business practices, which has amplified corporate interest in Sustainable Supply Chain Management (SSCM) (Hou et al., 2023). Mathematical models are valuable for decision-making and network structuring, however, to the best of the author's knowledge, the textile sector has seen limited analysis using such models. Additionally, 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. Jafari et al. (2017) offer a broad contribution to the study of sustainable closed-loop network by employing a 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 wastewaters and, lastly, maximizes employment. Although it does not deliver exact solutions, the results display its contribution for supply chains facing the water crisis.

The present work successfully integrates the three bottom line approach in a multi-objective optimization MILP model, each objective function representative of one of the three pillars. Besides the economic performance, the model also addresses the supply chain's water impact, as an optimization objective, proposing a broader approach to assess it. It employs the raw materials' water footprint, as already done by Cruz and Tan, (2023), albeit not specifically for the textile sector; 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; and the water consumption of other activities in the supply chain. Considering the raw materials' water footprint is especially important given that this work intends to study the impacts of introducing hemp as a raw material, in addition to cotton, as encouraged by many researchers (Duque Schumacher et al., 2020). The economic, environmental and social impacts will be assessed, however, despite addressing other environmental impacts of the supply chain, this work's environmental considerations are primarily focused on water. The social dimension will be measured by the employment generated in the supply chain, as previously accomplished by Jafari et al. (2017). Finally, a stochastic demand analysis is performed.

3. Problem Definition

The current work 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 considered, with particular focus on water impact in the environmental dimension. A generic mathematical model, as illustrated in Figure 1, was developed. As depicted, raw materials flow from suppliers to mills, where they are transformed into fabric, in a production first stage. Afterwards, the fabric is directed to factories for the last production stage, where 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 later transported by plane, boat or train, respectively. The figure also indicates the boundaries considered for each objective function. Although not modelled as an objective function, the overall environmental impact, that is, considering impact categories other than the water footprint, is also considered, for the agriculture and raw material processing, production and transportation activities.

Overall, given:

- Available locations of entities;
- Available capacities of suppliers, mills, factories and warehouses;

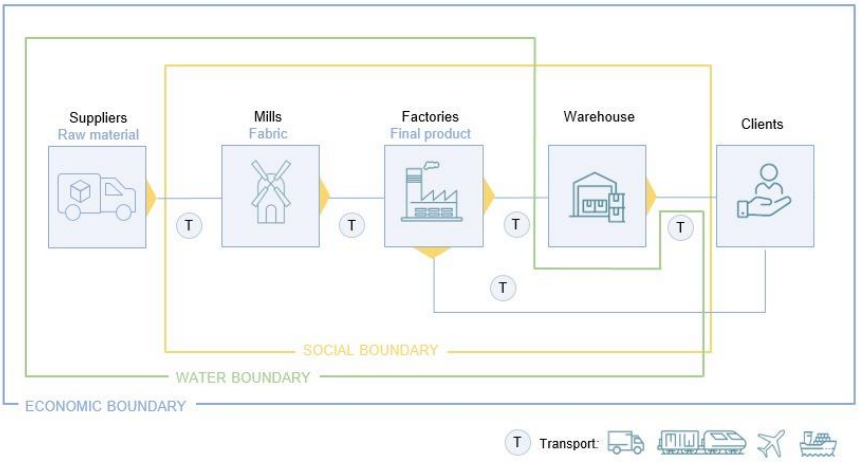

Figure 1: Supply chain representation.

- Initial inventory levels of final product;
- Number of necessary employees, per ton of product, in mills, factories, warehouses;
- Number of employees, per ton of transported product in every mode;
- Raw material costs, per ton of product;
- Production costs, per ton of 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 km.

The goal is to obtain:

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

So as to:

- Maximize Net Present Value (NPV).
- Minimize Water Impact.
- Maximize the annual number of jobs created by the supply chain, per year.

4. Mathematical Formulation

The decision variables of the formulated model are presented and described below, alongside their indices.

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)

Various constraints were integrated in the model. They pertained to material balances, in mills and factories and cross-docking in transport infrastructures; entity capacities, for supply, production and inventory; transportation constraints and, lastly, fulfillment of demand.

The economic objective function, defined in equation (1), is obtained from the maximization of the network's NPV, through the summation of each time period's cash-flow, at interest rate ir .

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

The variable $CashFlow_k$ is defined in equation (2), for each time period k, by the difference between the revenues, which corresponds to the final product's price p_i, in client i, multiplied by the flow of products to the clients and divided by the final product's weight fpw; and the total costs. The costs considered are raw material costs, production costs, stock costs, hub costs, transport costs, labor costs and lease costs. The cash-flow also accounts for the tax rate discount (tr).

$$\begin{aligned} &CashFlow_k = (1-tr) \cdot \\ &\sum_{\substack{t:(t,p,i,j) \in NetCon \\ (p,i,j):(p,i,j) \in F_{INcfp}}} (p_i \cdot \frac{X_{pijtk}}{fpw}) - \\ &RawMaterialCost_k - \\ &ProductionCost_k - \\ &StockCost_k - HubCost_k - \\ &TransportCost_k - LaborCost_k - \\ &LeaseCost_k, \ \ k \in K \end{aligned} \quad (2)$$

The water objective function translates the minimization of the supply chain's water impact, and it is defined in equation (3).

$$\begin{aligned} &\min WaterImpact = \\ &\textstyle\sum_{k \in K} \sum_{P \in P_{rm}} WaterImpact\_RM_{pk} + \\ &\textstyle\sum_{k \in K} \sum_{P \in P_{fab}} WaterImpact\_FAB_{pk} + \\ &\textstyle\sum_{k \in K} \sum_{P \in P_{fp}} WaterImpact\_FP_{pk} + \\ &\textstyle\sum_{k \in K} \sum_{t \in T} WaterImpact\_Trans_{tk} \end{aligned} \quad (3)$$

The total water impact corresponds to the summation of four different water impacts, expressed in equations (4), (5), (6) and (7).

$$\begin{aligned} &WaterImpact\_RM_{pk} = \\ &\sum_{\substack{t:(t,p,i,j) \in NetCon \\ (i,j):(p,i,j) \in F_{OUTsuprm}}} X_{pijtk} \cdot wf_{pi} \cdot \\ &ws_i, \ \ p \in P_{rm} \wedge k \in K \end{aligned} \quad (4)$$

Expression (4) considers the water impact associated with the suppliers, through the water footprint wf_{pi} of the raw materials (rm) and the water stress of the supplier's location ws_i.

$$\begin{aligned} &WaterImpact\_FAB_{pk} \\ &\qquad = \sum_{i \in I_m} \begin{matrix} W_{pik} \cdot wcf \cdot ws_i, \\ p \in P_{fab} \wedge k \in K \end{matrix} \end{aligned} \quad (5)$$

$$\begin{aligned} &WaterImpact\_FP_{pk} \\ &\qquad = \sum_{i \in I_f} \begin{matrix} W_{pik} \cdot wcfp \cdot ws_i, \\ p \in P_{fp} \wedge k \in K \end{matrix} \end{aligned} \quad (6)$$

$$\begin{aligned} &WaterImpact\_Trans_{tk} \\ &\qquad = \sum_{(p,i,j) \in NetCon(t,p,i,j)} X_{pijtk} \\ &\qquad \cdot dist_{ij} \cdot wct_t \cdot ws_i, \\ &\qquad t \in T \wedge k \in K \end{aligned} \quad (7)$$

Expressions (5), (6) and (7) consider the water impact associated with the production of fabric, the production of final product and the network's transportation, respectively. Equation (5) considers the water consumed to produce fabric wcf, equation (6) the water consumed to produce final product $wcfp$ and equation (7) the water consumed per transport mode wct_t. All three account for the region's water stress as well.

The social objective function, defined in equation (8), is obtained through the maximization of the number of jobs created in the network per year, with ny representing the number of years being analyzed.

$$\begin{aligned} &\max JobCreation = \\ &\textstyle\sum_{\substack{(p,i,k):(p,i) \in (V_{mfab} \cup V_{ffp}) \\ k \in K}} \frac{W_{pik} \cdot w_i}{ny} + \\ &\textstyle\sum_{\substack{(p,i,k):(p,i) \in (V_{wfp}) \\ k \in K}} \frac{S_{pik} \cdot w_i}{ny} + \\ &\textstyle\sum_{\substack{(t,p,i,j,k):(p,i,j) \in NetCon \\ k \in K \\ t \in T}} \frac{X_{pijtk} \cdot w_t \cdot dist_{ij}}{ny} \end{aligned} \quad (8)$$

It considers the number of jobs created in the manufacturing facilities, warehouses and in transportation activities, through w_i for the first two aspects and w_t for the last.

Finally, the total supply chain's environmental impact was obtained through equation (9), where the index c represents an environmental midpoint category.

$$\begin{aligned} &EnvImpact\_Category_c = \\ &\textstyle\sum_{p \in P_{rm}} EnvImpact\_RM_{pc} + \\ &\textstyle\sum_{p \in (P_{fab} \cup P_{fp})} EnvImpact\_Production_{pc} + \\ &\textstyle\sum_{t \in T} EnvImpact\_Trans_{tc}, \ \ c \in C \end{aligned} \quad (9)$$

5. Case Study

The developed model was implemented in the following case study regarding the supply chain of an apparel company with a market based in Asia and focused on jeans production. While the company currently only offers one family of final product, 100% cotton-made, new strategies to lessen the water impact are being explored, such as the introduction of a new type of final product, partially made of hemp.

Currently, the company's network has available 12 suppliers, 10 mills, 6 factories, 6 warehouses and 14 clients, all of them based in the Asian continent, except for two suppliers, one in Egypt and another one in Austria. The company does not own any of the production facilities or the warehouses, choosing instead to lease the facilities at the beginning of a 5 years' time span. There are also available 16 airports, 9 seaports and 10 railway stations. Goods can be transported through road, rail, air and sea. It was ensured that in every island there was, at least, one airport or seaport, to enable the connection to other countries. Each of the 14 clients has a demand that increases at a rate of 10% per year. All 12 suppliers provide RM1 (cotton), but only 6 provide RM2 (hemp). The price varies according to the supplier from which the raw material is purchased. The raw material that leaves the suppliers must reach a mill, to be transformed into fabric, either FAB1 or FAB2, and then to a factory to be transformed into a final product, respectively to FP1 or FP2. FP1 corresponds to 100% cotton jeans and FP2 corresponds to the hemp jeans, composed with a 70/30 cotton-to-cottonized hemp blend. There is no allocation of the production's capacity to a single type of fabric or final product. It is assumed that when it reaches the mill, the RM2 has already undergone a treatment process (cottonization), making the transformation process into fabric equal for both raw materials. Stock is only allowed in warehouses, and for final products. As for the transport requirements of the supply chain, the company relies on an outsourcing strategy. It counts on transport by truck, train, plane and boat, each mode with their respective costs per ton-km.

The water stress level considered for each region corresponds to the environmental indicator 6.4.2 built and used by FAO of the United Nations (FAO, 2022). The water footprint considered for RM1, for each supplier's country, was retrieved from the work of Chapagain and Hoekstra (2005), while the water footprint considered for RM2 was based on the study developed by Averink (2015). Finally, the water consumption values used for the production stages were based on a LCA conducted by Levi Strauss & Co. (2015) on a pair of Levi's® 501® and the consumption associated with the transports was retrieved from the Simapro Ecoinvent 3 database.

6. Results Analysis

The model was implemented in GAMS, version 42.4.0 on an 11th Gen Intel(R) Core(TM) i5-1135G7 @ 2.40GHz with 8 GB of RAM. Two supply chains were analyzed. The first exclusively trades cotton products, that is, RM1, FAB1 and FP1, while the second also trades FP2 composed of FAB2, made from RM1 and RM2.

6.1 Supply chain 1 – exclusively cotton products

Cases A, B and C focus on the first type of supply chain. Results for each case, presented in Table 1, were determined through a lexicographical approach based on the following priority order: maximizing NPV, minimizing water impact and maximizing annual job creation. This method presents efficient and non-dominated solutions.

For case A, the NPV obtained translates the maximum economic performance the company can achieve, and the water impact corresponds to the lowest the company can attain while maintaining that NPV. Case B delivers the highest NPV value the supply chain can reach after reaching the lowest possible water impact. For both, the social solution is the highest value attainable while keeping the NPV and water results already obtained. In case C the goal was to minimize the water impact while setting up the cash-flow per year as a non-negative value.

Table 1: Single optimization results – cases A, B and C.

	NPV (c.u.)	Water Impact	Social
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
Case C	0	6.66×10^6	1.73×10^7

From case A to B, the results are remarkably different. The NPV drops by 172% and it delivers a negative outcome. Despite reducing the water impact by 91%, case B is not an economically sustainable alternative for the company. It should be emphasized that the water impact comprises both the supply chain's water consumption and the impact associated with the region where that consumption occurs, measured by its water stress level. Case A's water impact corresponds to a water consumption of 8.17×10^7 m^3, whereas case B consumes 5.00×10^7 m^3 of water.

In case A 3 mills, in Bangladesh (M1), Egypt (M3) and India (M4), are leased and supplied by 5 suppliers. Of these, 3 are from the same country of the mills (S2, S5, S6) and the remaining 2 from Pakistan (S8 and S9). Given that the production cost is equal in every mill, the mills' leasing decisions are mainly influenced by lease, hub, labor and transport costs. Leasing 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 mostly influenced by the labor costs and 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 is more cost-effective to have a mill in this location, a more centralized position, as it drives transport costs down. It is also worth noting that Sri Lanka (S7) offers lower raw material prices than S2, however significant hub costs would be incurred when transporting goods by boat or plane to M1 or any mill. It is also due to the large hub costs that the main transport mode used in case A is truck. The only exception, when plane is used, occurs when the final products must reach the clients in islands.

The analysis for case B was valuable, despite not being an economic sustainable option, as it showed that the suppliers' selection, when optimizing the water impact, was more driven by the water stress level than the water footprint of RM1. The 4 suppliers chosen have the lowest water stress level, but not the lowest water footprint. It also showed that the sea and rail transport is preferred over the other modes.

There are three major costs, in case A, that together make up more than 80% of the company's total costs. The largest, representing 36% of the total, belongs to production operations, the second highest, with 27% of total cost, is attributed to labor and is closely followed by raw material costs, which represent 21% of the total.

Case C, although still not delivering a positive NPV, is a better comparison with case A, for water comparisons, than case B. Case C's water impact falls between the results for case A and B, and it corresponds to $4.97\text{x}10^7$ m^3 of consumed water. The additional $6.47\text{x}10^5$ of water impact, when compared to case B, is predominantly owed to the decision of using truck for most of the flows. However, when analyzing the variation of just the water consumption, from case B to case C, there is a reduction of $2.30\text{x}10^5$ m^3. Therefore, the increase in water impact can be primarily attributed to the water stress level of the regions where the network's activities occur.

As observed, the optimal solution for each objective creates trade-offs that should be explored to identify solutions that best fit the problem at hand. Multi-objective optimization was done through a lexicographic optimization and the ε-constraint method, which delivers the Pareto optimal solutions (Pareto Front). The Pareto Front was obtained for the combination of the economic and water objectives, in Figure 2.

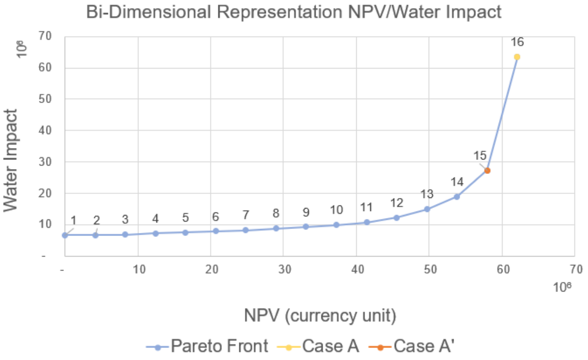

Figure 2: Multi-objective optimization: bi-dimensional representation of Water Impact against NPV.

The extreme points consist of case C and A. From the 15th to the 16th point (case A) there is clearly a more accentuated variation, displaying that, in those conditions, a 7% increase in the NPV leads to a water impact increase of 57%. This translates into a water consumption of 5.47E7 m^3, as opposed to $8.17\text{x}10^7$ m^3 in case A. This is mainly due to decisions regarding suppliers' selection. The results for the 15th point, or case A', are presented in Table 2.

Table 2: Single optimization results – case A'.

	NPV (c.u.)	Water Impact	Social
Case A'	$5.79\text{x}10^7$	$2.73\text{x}10^7$	$1.57\text{x}10^7$

6.2 Supply chain 2 – introduction of hemp fiber

This supply chain also includes RM2, FAB2 and FP2. Case D corresponds to the best performance for the economic objective function while case E delivers the best solution for the supply chain's water impact, assuming a non-negative cash-flow per year (similarly to case C). The results can be seen in Table 3.

Table 3: Single optimization results – case D and E.

	NPV (c.u.)	Water Impact	Social
Case D	$6.26x10^7$	$5.91x10^7$	$1.11x10^7$
Case E	0	$5.99x10^6$	$1.53x10^7$

Case D's network is similar to case A's, apart from two extra suppliers in China, which supply RM2. Case E also presents an extra supplier in India, comparatively to case C.

In case D, RM2 is purchased from China (S3 and S4) as it offers the cheapest price for any raw material. It is precisely due to this that their entire supply is purchased every year. Since the next best prices belong to RM1, and the goal is to maximize NPV, the quantity purchased of RM2 remains constant throughout the 5 years. In 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. These suppliers have the lowest water stress level out of all the available ones. However, for example 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 be indicative, as previously mentioned, that the water stress level has a stronger influence on the supplier's selection than the raw material's water footprint.

In case D, the production level for FP2 is constant. Producing more would require more RM2, thus the contract with a new supplier, which was not cost-effective as the price for RM1 was lower than any other price for RM2. In case E, there is a higher production of FP2. Since RM2 is less water intensive, increasing FP2 production would most likely have a positive influence on the water impact minimization. FP2 represents 35% of the product mix in case D and 69% in case E.

The water impact results are also highly different between both cases. Case D's water impact relies on a water consumption of $7.81x10^7$ m^3, while case E's consumed water is $4.32x10^7$ m^3, which corresponds to a 45% decrease. Once again, by comparing the water impact variation with the water consumption one, it was concluded that the water stress level plays a major role in the water impact of the supply chain.

As for the cases' costs analysis, a major difference pertains to the raw material and transport costs. From case D to E, the former increases 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. This contrast is also because, to produce FP2, there is a need for both RM1 and RM2.

For the multi-objective optimization of this supply chain, a new Pareto Front was generated, in Figure 3, with the extreme points representing case E and D.

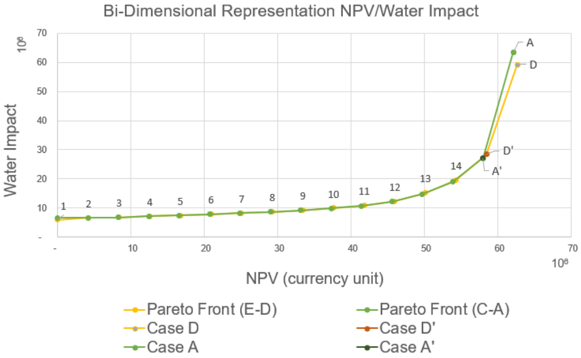

Figure 3: Multi-objective optimization: bi-dimensional representation of Water Impact against NPV (comparison between Pareto Front (C-A) and Pareto Front (E-D)).

The figure also depicts the Pareto Front obtained for the supply chain previously analyzed.

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, case D showcases an improvement from case A in all three objective functions and in the environmental impact, also considered. Nonetheless, due to the significant variation between the 15th (case D') and the 16th (case D) points, the results for case D' were looked into and are displayed in Table 4.

Table 4: Single optimization results – case D'.

	NPV (c.u.)	Water Impact	Social
Case D'	$5.84x10^7$	$2.84x10^7$	$1.58x10^8$

It was found that the water impact of the supply chain decreases by 52%, which corresponds to a water consumption decrease from $7.81x10^7$ m^3 in case D to $5.03x10^7$ m^3 in case D'. Conversely, the NPV obtained at the end of the 5 years is 7% lower in case D', creating a trade-off. Case D' was compared to case A' and, although very similar, case D' delivers a higher result for the economical function (+1%) and a worse result for the water impact (+4%) than case A'. However, as it will be further detailed, case D’ outperforms case A’ in the social and environmental dimensions.

6.3 Social objective function

The social dimension includes the jobs created in mills, factories, warehouses and in the transportation sector. Table 5 shows all social results.

Table 5: Social results for all cases analyzed.

	Social
Case A	$1.06\text{x}10^7$
Case B	$8.65\text{x}10^7$
Case C	$1.73\text{x}10^7$
Case D	$1.11\text{x}10^7$
Case E	$1.53\text{x}10^7$
Case A’	$1.57\text{x}10^7$
Case D’	$1.58\text{x}10^8$

The variations observed between cases directly derive from the jobs created in warehouses and in the transportation sector. The noticeable difference between the quantity of jobs created between case A, when NPV is maximized, and case B, when water impact is minimized, is mainly due to the difference of jobs in the transportation sector. In case B, the preference for boat and train, both of which require significantly more workers than truck and plane, increases employment considerably. With the introduction of hemp, the supply chain’s social impact is improved by 5%, from case A to D. Case D’ presents the highest result achieved, 1318% higher than in case D. This is because case D’ has the largest quantity of flows and supplier, and because it makes use of all available transport modes.

6.4 Environmental impact

The environmental analysis conducted revealed that the lowest environmental impact is observed in cases A ($2.19\text{x}10^6$) and D ($2.13\text{x}10^6$), where economic optimization is prioritized. The environmental results for cases B, C and E, which minimize the water impact, are higher, mainly due to the increase in the quantity of flows and, consequently, transport. Moreover, although the differences are 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.

6.5 Stochastic demand analysis

A stochastic demand analysis was conducted for case D which noted that two additional entities were required, one supplier and one factory, when compared to a deterministic demand. There was a reduction of 7% in the NPV, of 3% in the water impact and the social benefit increased by 10%.

6.6 Recommendations

Should the company intend to maintain its current line of products, represented by FP1, a significant improvement can be achieved in its water impact (-57%) if the company adopts the network and decisions made in case A’, instead of case A. It is advised that, should the economic toll of 7% from case A to A’ be considered too high, the managers should establish a threshold for the maximum sustainable NPV loss the company would be willing to undertake, given that, according to the multi-objective optimization, from the best economical outcome to the recommended scenario, it is expected that a small decrease in the NPV will be counteracted with a large decrease in the water impact. As for the incorporation of hemp (RM2) and FP2 in the product-mix, the results obtained (case D) suggest that it would be a rewarding alternative to trading only FP1, on all counts. The NPV would increase by 1% ($5.36\text{x}10^5$ c.u. more), the water impact decrease by 7%, which corresponds to less $3.60\text{x}10^6$ m^3 of consumed water, and the social and environmental benefits would increase by 5% and 3%, respectively. Finally, assuming that the company is committed to introducing hemp, a further step could be taken to achieve an even lower water impact. Adopting the decisions made in case D’ would be reaching one of the possible compromises alluded to above, when discussing case A’, that slightly lessened the NPV and water impact trade-off. This way, the company could still significantly reduce its water impact to $2.84\text{x}10^7$, and its water consumption to $5.03\text{x}10^7$ m^3, while its NPV would only be reduced to $5.84\text{x}10^7$ c.u..

7. Conclusion

Driven by the urgent global water crisis, investing in the field of sustainable water management strategies in supply chains is evident. This work contributes with a strategic decision support tool for the planning and design of a supply chain network, through a muti-objective MILP model. The model was implemented in a case study of an apparel company, to optimize the company’s economic performance, water impact and employment generation. One of the main contributions of this work relates to the water impact objective. Through the water footprint, water consumption and water stress level, the decisions made 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. Future work can extend the current model by focusing more on the social dimension and employing the ε-constraint method to derive optimal solutions between the economic and social objectives, as well as water and social objectives. The environmental assessment could also be included as an objective function and optimized simultaneously with the other three objective functions. Lastly, it is encouraged that other textile fibers, besides hemp, are investigated further as alternatives for the water-intensive cotton. Employing the model developed in this work would allow to assess the economic, water and social impacts of incorporating other fibers in a textile supply chain.

8. Bibliography

Andre, C. M., Hausman, J. F., & Guerriero, G. (2016). Cannabis sativa: The plant of the thousand and one molecules. *Frontiers in Plant Science*, *7*(FEB2016).

Averink, J. (2015). *GLOBAL WATER FOOTPRINT OF INDUSTRIAL HEMP TEXTILE*.

Chapagain, A. K., & Hoekstra, A. Y. (2005). *The Water Footprint of Cotton Consumption*.

Coherent Market Insights. (2022). Retrieved October 6, 2023, from https://www.coherentmarketinsights.com/market-insight/textile-and-apparel-market-5417

Cruz, D. E., & Tan, R. R. (2023). Cost and water footprint trade-off in a supply chain optimization model. *Clean Technologies and Environmental Policy*.

Duque Schumacher, A. G., Pequito, S., & Pazour, J. (2020). Industrial hemp fiber: A sustainable and economical alternative to cotton. *Journal of Cleaner Production*, *268*.

Environmental Audit Committee. (2019). *Fixing fashion: clothing consumption and sustainability Sixteenth Report of Session 2017-19 FIXING FASHION: clothing consumption and sustainability*.

ESPAS. (2015). *Global Trends to 2030: Can the EU meet the challenges ahead*.

FAO. (2022). Retrieved May 3, 2023, from https://tableau.apps.fao.org/views/ReviewDashboard-v1/country_dashboard?%3Aembed=y&%3AisGuestRedirectFromVizportal=y

Ritchie, H., & Roser, M. (2017). *Our World in Data*. https://ourworldindata.org/water-use-stress

Hou, Y., Khokhar, M., Sharma, A., Sarkar, J. B., & Hossain, M. A. (2023). Converging concepts of sustainability and supply chain networks: a systematic literature review approach. *Environmental Science and Pollution Research*, *30*(16), 46120–46130.

Jafari, H. R., Seifbarghy, M., & Omidvari, M. (2017). Sustainable supply chain design with water environmental impacts and justice-oriented employment considerations: A case study in textile industry. In *Scientia Iranica E* (Vol. 24, Issue 4).

Kaur, G., & Kander, R. (2023). The Sustainability of Industrial Hemp: A Literature Review of Its Economic, Environmental, and Social Sustainability. In *Sustainability (Switzerland)* (Vol. 15, Issue 8). MDPI.

Levi Strauss & Co. (2015). *THE LIFE CYCLE Understanding the environmental impact of a pair of Levi's ® 501 ® jeans*.

Li, X., Ren, J., Wu, Z., Wu, X., & Ding, X. (2021). Development of a novel process-level water footprint assessment for textile production based on modularity. *Journal of Cleaner Production*, *291*.

Morgan, A. J., Luthra, P., Parma, M., & Petrie, L. (2022). *Water stewardship in apparel and textiles – Part I, Water and the Industry's value chain. WWF-Germany.*

World Bank. (2018). Retrieved March 16, 2023, from https://knowledge4policy.ec.europa.eu/foresight/topic/growing-consumerism/more-developments-relevant-growing-consumerism_en

Zimniewska, M. (2022). Hemp Fibre Properties and Processing Target Textile: A Review. In *Materials* (Vol. 15, Issue 5). MDPI.