Optimizing Supply Chain Management Practices to Reduce Water Loss Related With Food Waste

Inês Madeira Ferreira
ines.madeira.ferreira@tecnico.ulisboa.pt

Instituto Superior Técnico, Lisboa, Portugal

November 2023

Abstract

With increasing environmental sustainability concerns, food companies seek to provide their clients with more sustainable products. Agriculture accounts for a significant percentage of global water consumption, and food loss throughout the supply chain further exacerbates water usage. To address these challenges, this work presents a decision support tool based on a multi-objective mixed integer linear programming model for supply chain design and planning, focusing on food waste and water consumption. Stochastic programming was used to deal with uncertainty in demand. The model was validated using a real case study in the fried potato industry and the new network proposed was analysed based on the ϵ-constraint method. The proposed model considers the entire supply chain, from crop cultivation to markets, while accounting for the water stress of each region where supply chain activities occur, and the water-use efficiency of production facilities. Key decisions include suppliers and raw materials selection, supply and production planning, product mix definition, production facility location and allocation and deciding whether to invest in technologies to reduce waste. The primary objectives are to minimize water environmental impact using a life cycle assessment (LCA) approach that considers water used in various supply chain activities, minimize food waste and parts not used for final production and maximize economic performance. The results suggest that food waste is more critical near consumers, accounting for 57% of water lost when food is wasted. By redefining product mix and supplier selection, water consumption and total waste can be reduced by 28% and 14%, respectively.

Keywords: water scarcity, food waste, supply chain design and planning, sdg6, multi-objective

1. Introduction

Due to the rapid development of the industry in recent years, the world's population has grown exponentially in the last century, leading to increased consumer demands and consequently more significant pressure on all industries in the most diverse sectors. One of the biggest problems associated with growing consumer demand is the lack of resources on the planet (Chartres and Sood, 2013). One of the primary concerns is the substantial quantity of food and water required to sustain the world's inhabitants in the coming years, particularly with the projected population of 9 billion by 2050. It is projected that the demand for food by 2050 will increase by over 60% compared to the requirements of 2005-2007 (Chartres and Sood, 2013) and it is anticipated a yearly increase in water demand by 1%. Access to clean water and sanitation (6th goal of the sustainable development goals) to promote hygiene habits is essential for health and well-being and some progress is being made towards providing access to this resource to the entire population, however, even so, the effort must be intensified, otherwise, billions of people will continue to lack access to water by 2030 (UN, 2022).

Beyond improving the use and management of water resources, it is necessary to extend this management to other sectors that are intrinsically related to water consumption. One such area is agriculture and food production, where it is currently estimated that 70% of the freshwater withdrawn for human activities is used.

Water scarcity and food waste are two concepts that are closely intertwined. All wasted food represents significant water losses considering that all the water used to produce and transport that food is also wasted. This means that food waste and loss in regions experiencing water stress can exacerbate water scarcity and contribute to water shortages. Reducing food waste and loss helps improve water management practices, which can ultimately help alleviate water stress. It emphasizes the urgent need to address food loss and waste as a critical factor in reducing water scarcity and ensuring sustainable food systems (Marston et al., 2021).

The food industry is a complex system that encompasses the entire supply chain (SC), from crop production to the final consumer. Throughout this process, it is estimated by the United Nations that approximately 13.3% of food was lost globally after harvest in the year 2020. Depending on each industry, these losses occur at various stages, including on-farm, during transportation, storage, wholesale, and processing (UN, 2022).

2. Literature Review

The concepts of food waste and loss are related to the decrease in the quantity or quality of food for human consumption. The portion of food that is wasted is redirected for animal feeding, used to generate bio-energy or it is dumped into land. Usually, food is wasted or lost in agriculture, post-harvest, processing, distribution, storage and near the final consumers. Several factors can contribute to food loss, which refers to the decrease in weight and quality of food that does not reach the final consumer and was produced for human consumption. These factors include system malfunctions, inadequate storage, improper food handling, inadequate packaging, and inefficient cooling systems. Food waste, on the other hand, pertains to food that is discarded or removed from the supply chain despite being edible for human consumption, which is usually a result of poor stock management, and neglect that leads to expired food or even consumer waste (Rezaei, 2017).

Given water's increasing scarcity, its consumption throughout supply chain activities is also critical in the agri-food sector. Assessing and managing water usage in this sector is fundamental, and optimization models are effective tools for this purpose. The few models that evaluate water consumption are focused on single products, without exploring variations of the same product, such as different ingredients or different types of raw materials, that can lead to different requirements regarding water use. In fact, much of the research on water consumption in the agri-food sector is mainly focused on evaluating the water requirements for crops. However, there is a noticeable gap in studies that assess water consumption during the whole processing phase until reaching the final consumer. For instance, a study by Motevalli-Taher et al., 2020 is focused on evaluating the water consumption for wheat crops according to each crop's requirements. However, the indirect water use in activities such as transportation and processing in factories is not considered, nor is the water availability in each region.

When evaluating water requirements for different products, it is also relevant to consider the waste and losses associated with each one, that can arise from varying susceptibilities during transport and storage, or different processing characteristics. Previous studies in operations research related to food waste primarily focus on valorising that waste by producing products from unused parts. However, current research falls short in quantifying waste based on individual product characteristics, (Krishnan et al., 2022), that differ according to the processing techniques used. By integrating data on water consumption with losses and waste throughout the supply chain, we can assess the impact of water loss linked to food waste. Using this information, supported by comprehensive optimization models, more informed strategic and tactical decisions can be made, leading to enhanced water resource management (Agnusdei et al., 2022).

In the literature, from the models identified, it becomes evident that existing research has extensively explored the economic and social aspects of the triple bottom line of sustainability. Some optimization models primarily focus on minimizing costs (Allaoui et al., 2018) or maximizing profit. However, there appears to be a gap in the literature when it comes to models that consider Net Present Value (NPV), which would allow for a more explicit inclusion of long-term investments in technologies that improve water-use efficiency or reduce waste, for instance. Those investments can be applied in factories or agricultural fields. The models that include the social aspects are mostly focused on the number of jobs created considering a certain network.

No paper was found that simultaneously addresses food waste and water consumption, nor considers the water footprint from food waste in the decision-making process. Carbon emissions are the predominant environmental concern, due to the extensive regulations surrounding this topic. Those studies considered the emissions to establish facilities (suppliers, factories, and distribution centres), as well as the emissions related to transportation. Moreover, it is also common to consider the emissions related to warehousing and inventory handling (Sharifi et al., 2023).

Four articles were identified related to water consumption or water impact. The model developed by Sharifi et al., 2023 considers water use as well as other sustainable indexes in an objective that maximizes sustainability for the supplier's choice. The main decisions are focused on the supplier's selection, if a processing plant is established in a certain location or if a distribution centre is selected in a certain area. However, water consumption assessment is only considered for the supplier's choice. Aside from that, Allaoui et al., 2018 propose a model that in one objective function intends to minimize the CO_2 emissions while minimizing the water consumption related to maintaining, closing or opening distributor and transformer sites and the variable consumption from suppliers, distributors and transformers. This study evaluates supplier, transformer, and distributor candidates based on multiple sustainability criteria, including waste generation. Tang et al., 2021 in their study incorporate an index related to the risk of water shortage and the results demonstrate that it is possible to solve water conflicts caused by unfair water distribution and water shortage risks by reallocating water resources. Motevalli-Taher et al., 2020 presents a study that is focused on minimizing water usage on any farm for wheat SC, by considering different water source priorities and different cultivation modes with different water consumption, however, it is only focused on the supplier's stage.

A study involving potato production in Great Britain emphasizes the importance of measuring water consumption considering a map of water scarcity (Hess et al., 2015). By analysing crop production from this point of view, it is possible to establish ”hotspots” of water-related risk for potato production.

In relation to waste, two papers were identified. However, none of these studies approach waste considering the percentages that are lost throughout the entire supply chain. In a study within the field of mango pulp SC (Krishnan et al., 2022), where it is analyzed a network for processing and transforming the waste of mango, it is considered the possibility of using the parts wasted for other applications and measuring the environmental impact in terms of greenhouse emissions. However, in conclusion, the researchers suggest that the model should be extended to include the analysis considering the product-specific parameters and that way, a possible approach would be to study the waste derived from each product or process used. Deng et al., 2022, studied food systems by optimizing them, balancing the economic perspective, CO_2 emissions and maximizing jobs created. That way, it is possible to produce no waste since the quality is preserved during transportation. Several studies are focused on ways to improve processes that lead to waste processing or lead to its reduction regarding perishable items, however, there are no optimization models focused on following the waste that occurs along the SC, according to products or processes used, which is the goal of the study presented.

The literature review identified several research gaps in the design of sustainable food supply chains. Few studies contribute to solutions to reduce food waste according to product characteristics. When assessing the environmental impact, the focus is mainly on gas emissions and few studies consider water consumption and the level of water scarcity in each region. There is also a lack of research to measure the environmental footprint of operations considering different product characteristics. Lastly, few studies consider demand uncertainty while designing food SC in a sustainable context. To deal with the problem of facility location, this work suggests using an optimization model that considers the water stress level index, the water footprint of agri-food per crops and per country, and the water consumption of activities along the supply chain. The percentages of waste and losses according to each stage of the supply chain and the raw materials utilization along the processing phase when producing different products are relevant variables to analyze. By pinpointing the products that are most effective in reducing food waste and minimizing environmental impact on water, comparisons can be drawn regarding the water footprint of food losses. These findings can motivate decision-makers to invest in techniques to reduce food waste to deal with water scarcity issues.

3. Methodology

To address this gap in the literature, the problem being analyzed aims to optimize a food supply chain by minimizing its environmental impact in terms of water and resource usage while simultaneously maximizing economic performance. A mathematical model is developed to guide the decision-making process regarding the supply chain network design. This model is used to define a possible To-Be solution and compare it with the results associated with the As-Is solution. To validate the model, a real-world case study is applied in the deep-fried potato industry. The model considers a generic network that establishes the exchanges between the different sectors of the food supply chain, as illustrated in Figure 1. It is considered water consumption for suppliers operations, manufacturing processes, indirect consumption for transportation between facilities, storage in refrigerated warehouses and packaging. Losses are considered for crop development, post-harvest operations, and manufacturing processes, while waste is considered for the customers stage.

The objective of the model is to define the optimal locations of the factories and to select suppliers based on the locations of the crops. Establishing different possible final products (FPs), using different raw materials (RMs), can lead to optimized results regarding water and waste concerns. Different crops may have varying water consumption rates depending on the country or region, and

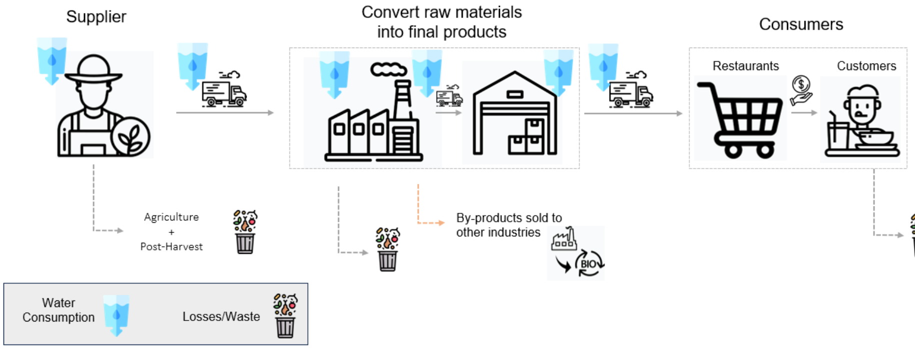

Figure 1: Generic supply chain for the food industry.

even different varieties of the same crop can have distinct water requirements. This same logic applies to factories, where each one may have different water-use efficiencies. Different products can also lead to different water-use during the processing phase. This study aims to maximize the parts of RMs that are effectively used for FPs, however, some parts cannot be used and there are two destinies possible: waste or use those by-products for other purposes. In this case, parts of the RMs can become trapped in the water flow during processing. As a result, the possibility of investing in technology to recover these by-products from wastewater is considered. The quantities of each FP produced are also optimized, in order to minimize food losses and water consumption.

There are four relevant parameters in the model developed:

- Water stress index (per country);
- Water footprint associated to each crop and country where it is produced;
- Water consumption for transportation, warehousing, packaging and production;
- Percentage of Losses that occur, on average, on each stage of the SC, parts of products used or not for each type of FP and waste near consumers level (Rezaei, 2017);

Water stress is measured using a percentage-based index provided by "Aquastat", a global information system on water and agriculture developed by the Food and Agriculture Organization (FAO, 2020). When assessing the water footprint of activities along the food supply chain, various LCIA (Life Cycle Impact Assessment) methods were analyzed. LCIA is a methodology used to evaluate the potential environmental impacts associated with the life cycle of a product. From this analysis, the ReCiPe2016 method was selected as the preferred LCIA method. The method incorporates a characterization factor known as the water consumption potential (WCP), which is expressed as the amount of water consumed (m3) per unit volume of extracted water (m3) (Huijbregts et al., 2017). The problem under analysis is based on the following assumptions and the mathematical formulation was developed considering them.

Overall, given:

1. Location of crops, where each raw material is sourced;
2. Maximum capacity for each supplier (tons);
3. Maximum and minimum production capacity in each factory (tons);
4. Number of employees per factory;
5. Cost per hour for each employee in each factory (EUR);
6. Purchase cost of each raw material (EUR);
7. The selling price of each final product and by-products (EUR);
8. Transportation cost (EUR per tons.km);
9. Market demand in each period of time (tons);
10. Bill of Materials (BOM) (tons);
11. Losses in Agriculture, Post-Harvest and during the processing phase (%, compared to the products that arrive at each stage);
12. Waste generated by consumers (%);
13. Water-stress level of each location (%);
14. Amount of water used to produce the raw materials (water footprint) (m^3/ton);
15. Amount of water used to process one ton of frozen potatoes (water-use efficiency) in each factory (m^3/ton);
16. Water-use for transportation (m^3/ton.km) and warehousing (m^3/ton);
17. Distances between entities (km);

The goal is to determine:

1. The quantity of raw materials cultivated based on the needs of the factories;
2. The quantity of raw materials supplied in each area;

3. The quantity of final products of each type produced in each factory;
4. The location of each factory being used;
5. The amount of water lost due to food losses;
6. The amount of food losses and waste;
7. Water consumption along the supply chain;

So as to:

1. Minimize Water Environmental Impact which takes into account water-use and water stress in each region;
2. Minimize the food loss or waste, which is represented by the portion of raw materials not used for final products as well as losses or waste;
3. Maximize the network's Net Present Value (NPV);

3.1. Mathematical Formulation

In the following section, the mathematical model is summarized. The model is then applied to a representative case study in the fried potato industry for validation purposes.

- $X_{m,io,id,t}$: Flow of product m from entity io to entity id in time period t;
- $P_{m,g,i,t}$: Amount of final product m produced with technology (cut type) g in entity i in time period t;
- $Aux1_{i,t}$: Amount of products produced in factory i that have the technology to treat wastewater in period t;
- $TechWaterTreat_i$: 1 if technology is installed in a factory i;
- $Tes_{i,t}$: 1 if entity i is being used ;

The constraints defined are related to demand, bill of materials, materials balance, capacities and limitations in the production of each FP.

To analyze the economic performance of the network, an objective function was defined to maximize the Net Present Value (NPV). This formula considers the costs and revenues and allows the decision-maker to compare the economic impact of different decisions. The NPV is given by the expression 1. The CF_t in the equation are determined by considering the earnings generated during each specific period, including not only the earnings but also, the salvage value, as expressed in equation 2. In this case, the investment is only associated with a technology to recover starch from water, and it is assumed that it holds no value in the last period.

$$\max \quad NPV = \sum_{t \in T} \frac{CF_t}{(1+ir)^t} - FCI \tag{1}$$

$$CF_t = \begin{cases} NE_t, & \forall t = 1, ..., NT-1 \\ NE_t + sv * FCI, & t = NT \end{cases} \tag{2}$$

The net earnings (NE) are defined, for each time period, by the difference between the revenues and the total costs as presented in expression 3. The sales are given by the sum of the revenue obtained by selling the FPs and by-products, while the costs account for manufacturing and labour costs, transportation and raw materials. The manufacturing costs are related to facilities costs, such as water, energy and other costs associated with the factory, including maintenance etc.

$$\begin{aligned} NE_t = {} & (1-tr)[FPSales + FlakesSales \\ & + StarchSales - RMCosts \\ & - TransSupFacCost \\ & - TransFacWhCost \\ & - TransWhMarketCost \\ & - LabourCost - ManufacturingCost \\ &] + tr * DP_t \end{aligned} \tag{3}$$

Finally, equation 4 describes the depreciation of the investment over time (DPt). The fixed capital investment (FCI) is given by expression 5 and it is characterized by the number of factories that have a technology installed times the cost of installing it.

$$DP_t = DepreciationRate * FCI \tag{4}$$

$$FCI = \sum_{i \in i_f} TechWaterTreat(i) * TechCost \tag{5}$$

To analyze the network obtained from an environmental perspective, it is intended to minimize water consumption while considering the water stress level of each location ($wstress_i$) (expression 6). The goal is to reduce water usage in areas suffering from water scarcity. The objective function was divided into four levels: suppliers, factories, warehousing activities, and transportation. For each sector, the water environmental impact is determined by multiplying the quantity of water consumed (water footprint and water-use efficiency) by the water stress level of each location.

The third objective function aims to minimize the quantity of raw materials that are not used for the final products. Equation 7 considers the quantity of final products that are wasted in each market according to each country's waste patterns, plus the amount wasted during production, the by-products originated, plus the amount used to produce potato flakes (by-product type) minus the amount of starch (by-product type) recovered, according to the existence of a specific technology that recovers it from wastewater. It also considers the percentages of RMs that are lost near the farmers, in the post-harvesting process and during the crop development.

$$
\begin{aligned}
\min & \sum_{(m,t,i,id):m\in m_{rm}\wedge(m,i,id)\in F^{OUTsup}} (wfp_{m,i} \\
& * X_{m,i,id,t} * wstress_i) \\
& + \sum_{(i,m,t,g):(i,m)\in V^{fac\text{-}fp}\wedge(m,g)\in H1} (wuse_{(m,i)} \\
& * P_{m,g,i,t} * wstress_i) \\
& + \sum_{(m,i,id,t):(m,i,id)\in F^{INmfp}} (wpackwh \\
& * X_{m,i,id,t} * wstress_i) \\
& + \sum_{(m,i,id,t):(m,i,id)\in F^{OUTsup}} (X_{m,i,id,t} \\
& * distsf_{i,id} * wtrans * wstress_i) \\
& + \sum_{(m,i,id,t):(m,i,id)\in F^{OUTfac}} (X_{m,i,id,t} \\
& * distfw_{i,id} * wtrans * wstress_i) \\
& + \sum_{(m,i,id,t):(m,i,id)\in F^{OUTwh}} (X_{m,i,id,t} \\
& * distwm_{i,id} * wtrans * wstress_i)
\end{aligned} \tag{6}
$$

$$
\begin{aligned}
\min & \sum_{(i,m,t,io):(i,m)\in V^{m\text{-}fp}\wedge(m,io,i)\in F^{INmfp}} (X_{m,io,i,t} \\
& * Losses\_Market_{i,m}) \\
& + \sum_{m,n,g,i,t:(n,g)\in H1\wedge m\in m_{rm}\wedge(n,i)\in V^{facfp}} P_{n,g,i,t} \\
& * BOM^{rm}_{m,n} * Used\_byprod_n \\
& + \sum_{m,n,g,i,t:(n,g)\in H1\wedge m\in m_{rm}\wedge(n,i)\in V^{facfp}} P_{n,g,i,t} \\
& * BOM^{rm}_{m,n} * Used\_flakes_n \\
& + \sum_{m,n,g,i,t:(n,g)\in H1\wedge m\in m_{rm}\wedge(n,i)\in V^{facfp}} P_{n,g,i,t} \\
& * BOM^{rm}_{m,n} * L\_potato \\
& - \sum_{t,i:i\in i_f} Aux1_{i,t} * starch\_rec \\
& + \sum_{m,i,id,t:m\in m_{rm}\wedge(m,i,id)\in F^{OUTsup}} (\\
& \frac{X_{m,i,id,t}}{1 - L\_Agri - L\_PHarv} - X_{m,i,id,t})
\end{aligned} \tag{7}
$$

4. Case Study and Data

The case studied pertains to a global fast-food chain. The boundary is the European market and all entities are located there. The focus is deep-fried frozen potato production, one of the most important options on the menus and a main factor attracting customers. Deep-fried potato production for the European market is predominantly assured by two companies (A and B) dedicated to the potato industry. The focus is to study the potato supply chain associated with the fast-food chain, one of the most important clients in this sector. Each company owns factories where they produce different products. After leaving the factories, the products are stored in nearby warehouses, for a week, for a process called colling-down. Each factory has its own warehouse where all products pass before being delivered. Figure 2 presents the locations of each factory and the possible suppliers associated to the production of each FP type.

Companies A and B have different production capacities for each factory and there are different types of final products produced in each location. Transportation between entities is assured by trucks.

The case study examines the impact of introducing new final products (FP3, FP4, FP5, FP6). Note that FP3, FP4 and FP5 are made of potatoes, while FP6 represent veggie fries, using beetroot, parsnips and carrots. Currently, FP1 and FP2 are considered the main products sold. Table 1 presents the differences between the FPs identified. Note that Potatoes X and Y are different varieties and the second one consumes less 20% of water when compared to the first one. One of the main distinguishing factors among the products offered by the company is their cut that leads to different quantities of by-products obtained. Observe that for the FP3, FP4 and FP5, the peel is used, which will lead to high water consumption for the cleaning process. However, by using the peel the percentages of raw materials used for the FP increase, since the peel represents 8% of the potato. Cutting the potatoes in wedges is typically done using smaller potatoes. Thus, this approach minimizes waste since it is possible to use smaller potatoes that are normally rejected. Nowadays, each of the two companies requires 2.5 Kg of raw potatoes to produce one kg of frozen deep-fried potatoes (for FP1 and FP2). Note that the potato loss corresponds to 4% since both companies do not have enough resources to recover all the by-products. As potato processing takes place in water, certain parts become immersed, presenting an opportunity for reducing losses through water treatment. The quantity of by-products obtained from potatoes can vary depending on the cutting technique. FP6

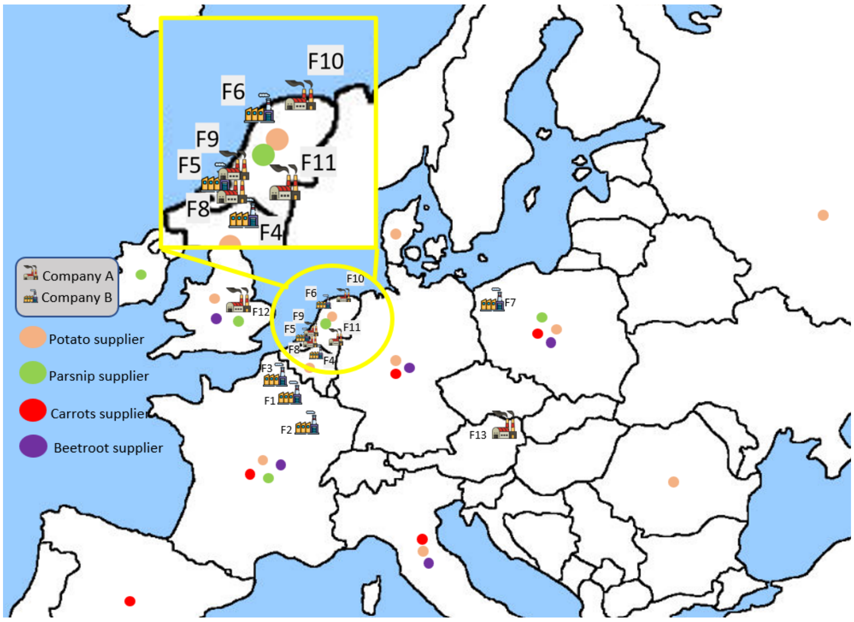

Figure 2: Factories where the two companies' operations currently take place and the possible suppliers' location.

is introduced to study the benefits regarding water footprint associated to different crops.

Table 1: Final Products Characterization.

FP	Raw Material	Shape
FP1	Potato X	Sticks
FP2	Potato Y	Sticks
FP3	Potato X	Slices
FP4	Potato Y	Slices
FP5	Potato X	Wedges
FP6	Beetroot, Parsnips, Carrots	Sticks

The data collected on water footprint for various crops was collected from Agri-footprint database, using ReCiPe2016 method, considering a French national market mix. Based on the information available in this database, it was estimated the water footprint for each raw material for each location sourced. A country's water stress level is determined by comparing its annual total water withdrawal to its total renewable freshwater resources, using Aquastat index. Each factory has a water-use efficiency associated. These values were estimated based on the information provided in the sustainability reports of the companies aside from the values available through the ReCiPe2016 method using Agribalyze database. Water use for packaging and warehousing was estimated using ReCiPe2016 methodology from the Agribalyse database. The values related to water consumption for transportation were collected from the Ecoivent database. Waste percentages were estimated using data from a comprehensive global study on food supply chains (Rezaei, 2017). A new technology can be implemented to allow the recovery of around 2% of starch from wastewater. It is considered that there are losses during the crops development (around 20%) and during post-harvest processes (6%) considering the initial quantities cultivated, and also during the production process (around 4% of the products that arrive at the factory). Waste occurs near the final consumers and varies according to each market (between 4 and 17%).

5. Results

5.1. As-Is

The current network structure consists of four suppliers: France, Germany, Belgium, and the Netherlands. Additionally, the use of 8 specific factories is considered. Using this structure, various approaches can be formulated to determine the flows. The As-Is solution is determined by maximizing the NPV for the network defined. In the current solution, the final products considered are only the traditional sticks using both potato varieties (FP1 and FP2). Table 2 presents the results obtained for this solution (case A1). It also represents the results associated with water and waste (B1 and C1) objective functions, considering the As-Is network. The cells on the diagonal represent the best values achieved. The values obtained to waste and RMs not used in the final products remain constant since this parameter only changes by introducing different types of final products, with different cuts leading to different usage of RMs.

Case A1, in table 2, represents the As-Is solu-

Table 2: Results obtained for As-is Solutions, To-Be solutions and proposed network.

As-Is			
Objective	NPV (M EUR)	Water Impact	Waste (M tons)
A1: Maximize NPV	985.31	3.61×10^9	17.77
B1: Minimize Water Impact	970.74	3.50×10^9	17.77
C1: Minimize Waste	985.31	3.61×10^9	17.77
To-Be			
A2: Maximize NPV	1154.42	2.99×10^9	14.69
B2: Minimize Water Impact	-23.19	1.82×10^9	15.46
C2: Minimize Waste/Loss	1140.67	2.95×10^9	14.07
Proposed Network			
Proposed Solution - Multi-objective	997.40	2.03 x 10^9	14.29
Improvement compared to As-Is (Max NPV)	+1.2 %	-41.9 %	-19.6%

tion for the comparative study. The results remain highly similar for cases B1 and C1, as the network structure is the same. It is noteworthy to observe that the water footprint values follow the order: Belgium $<$ Netherlands $<$ Germany $<$ France, and the cost of potatoes follows the order: Netherlands $<$ Belgium $<$ Germany $<$ France. Consequently, these rankings contribute to the similarity in outcomes for both objectives. Observing that, it is evident the need to redesign the network and introduce new FPs.

When minimizing the environmental impact on water resources, it is also produced FP1 that represents higher water footprint. The water footprint for potato variety X is lower in Belgium compared to, for example, variety Y in the Netherlands. This explains the production of products using potato variety X for case B1. Selecting the right supplier becomes more important than solely considering the water footprint of each potato variety.

As expected, the solution that minimizes water impact exhibits the lowest water volume: 175.600 M m3. The water consumption when maximizing the NPV is 175.682 M m3. Thus, with this network structure, it is only possible to reduce water consumption by 0.05%.

5.2. To-Be

Three distinct cases are identified by redesigning the network: maximize NPV (Case A2), minimize water environmental impact (Case B2), minimize food waste/losses and RMs not used for FPs (Case C2). The idea of introducing new products and redesigning the network can lead to improvements for each of the three different cases identified. Table 2 presents the lexicographical results, considering that in this problem, it is always assumed that the most relevant parameter is the NPV, followed by the water environmental impact and then the food waste/loss and RMs not used for FPs.

The results demonstrate that it is possible to improve the NPV by 17%, the water environmental impact by 48% and the waste and all the RMs not used for FPs can be reduced by 21%, when comparing the As-Is network and the To-Be proposals. When optimizing the new proposal of the network to reduce the water environmental impact it is possible to achieve an improvement of 39% (Case A2 vs B2), however, the NPV becomes negative showing that this solution is not recommended. Regarding waste, comparing cases A2 and C2, it is only observed a reduction of 4%. While this value may appear negligible at first glance, when we consider these quantities in terms of nutritional value, it becomes evident that this surplus can sustain 55 000 individuals over a span of 10 years.

The problem should be solved using multi-objective techniques. For that, it was applied the augmented ϵ-constraint method three times for each pair of objectives. Finally, considering the results obtained, it was developed a Pareto frontier considering the 3 objectives. By analyzing this Pareto front, 3 possible solutions emerged as potential solutions and comparing them, one was chosen to be deeply investigated. Table 2 provides the values related to the solution identified, suggesting a new network.

To achieve these results, the network structure for the new proposal involves the following suppliers: Belgium, the Netherlands, Poland, and Russia for potatoes; France, Ireland, the UK, the Netherlands, and Poland for parsnips; and Poland for carrots and beetroot. The main difference regarding the factories is that the production does not occur in Poland and more factories are used in the Netherlands. The final product distribution is 22.9% of FP1, 25.6% of FP2, 3.5% of FP3, 19.7% of FP4, 25.3% of FP5, and 3% of FP6.

By suggesting this solution, the idea is to decrease the quantity of RMs needed and better optimize resource utilization. It is verified a reduction of 12% in the amount of tubers that must be planted to meet the demand. Another relevant observation involves a significant decrease in waste within factories. With the implementation of the new network, waste corresponds to 43% when compared to the previous network. This reduction can be attributed to integrating technologies aimed at extracting starch from wastewater, implemented for all factories used. Lastly, near the consumer stage, it is verified an increase in waste levels of 2.5%, due to the introduction of new products, which can possibly lead to higher waste. Estimating this value accurately is complex and the correlation between the introduction of new products and waste levels is not necessarily linear. However, even considering this pessimistic scenario, the overall outcomes result in substantial improvements.

The proposed solution cuts water consumption by 28%, totalling 127.316 M m^3 over 10 years, thanks to reduced raw material needs and supplier selection. By introducing new FPs in the network, the waste can be reduced during the processing phase and also in the agriculture stage, accounting for a reduction of 15%. When converting it to nutritional value (in Kcal), it is estimated to provide sustenance for 120 630 people over a period of 10 years. The waste converted into water consumption (figure 3) decreases when compared to the As-Is solution. This occurs due to the overall optimization of water resources along the SC. It is evident that the waste near the final consumers (figure 3) represents 57% of the water wasted. When wasting food in this phase of SC it was consumed water for transportation, production, packaging, warehousing and agriculture. The same reasoning is applied to waste in factories, which means that when a product is wasted in this stage, it has already consumed water for production, transportation and agriculture. The most relevant reduction is the water associated with agriculture losses, which is minimized by choosing suppliers with lower water footprints, and FPs that consume fewer resources and lead to reduction of quantities lost. The total water footprint associated with food losses and waste for the To-Be network accounts for 22 M m^3, while for the As-Is network, the value reaches 42 M m^3.

To conclude that the solution presented is robust, a sensitivity analysis was performed for the water footprint of raw materials, water-use efficiency for production, suppliers' capacity and food waste in the markets.

The demand for frozen potatoes is estimated to grow 2.2% per year for each country, however, consumption patterns can change. A decrease in demand is unlikely but possible due to instability in Europe. Thus, a stochastic approach is followed to confirm the robustness of the model. Different scenarios are defined and identified by a new index 'sc' added to the following decision variables: $X_{m,i,j,t,sc}$, $P_{m,i,j,t,sc}$, $Aux1_{i,t,sc}$ and equations were adapted accordingly. Four different scenarios are considered: the base scenario, characterized by an annual demand growth of 2.2%, with a probability of 50%; scenario 2, characterized by an annual demand growth of 1.1%, with a probability of 20%; scenario 3, characterized by an annual demand growth of 4.4%, with a probability of 20% and scenario 4, characterized by an annual decrease in demand of 1%, with a probability of 10%.

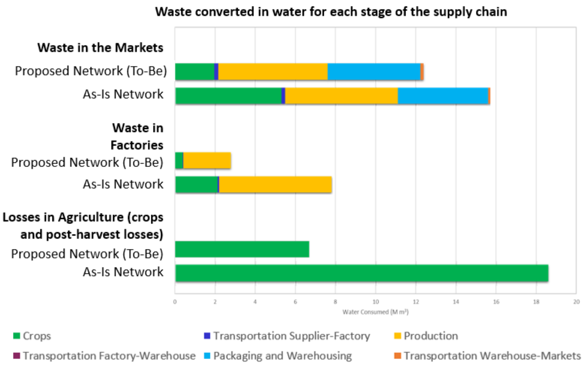

Figure 3: Amounts of raw materials wasted or lost converted in water (m^3) along the supply chain.

The model was optimized considering the economic objective and the results obtained did not reveal any significant changes. Overall, considering the scenarios tested, it is expected to obtain lower sales and an NPV slightly lower. This is related to the investment in technologies and the turnover related to it, since they are used according to the quantities of final products produced. However, the differences are not significant and reveal that the company continues to be profitable. The proposed network structure is robust in scenarios with lower demand.

6. Conclusions

The developed model contributes to the literature by considering both food waste and water scarcity in one tool. A multi-objective mixed integer linear model was developed considering three objectives defined for this case: maximizing NPV, minimizing water environmental impact, and minimizing food waste. It allows defining supplier locations, factories used for production, products to be produced and deciding whether to invest or not in technologies to reduce waste. Different networks are obtained by optimizing for each objective, with various entities involved. For a comparative study, initially, it was defined the As-Is solution by considering the FPs currently sold in higher quantities and establishing the suppliers and factories used. This approach primarily focused on maximizing NPV. Using the same network, it was examined how companies could enhance values related to water environmental impact and resource usage. Additionally, it was explored how the objective function values could be improved when redesigning the network. A multi-objective analysis was conducted, taking into account all three objectives by employing the augmented ϵ-constraint method, in order to identify a possible and feasible solution.

A stochastic approach was developed to deal with the demand uncertainty and it proves the robustness of the model.

This methodology allows the identification of a solution that represents a compromise between the three objectives defined. The economic performance was improved by 1.2%, the water impact was reduced by 41.9% and the waste and RMs not used for FPs were reduced in 19.6%. The NPV increased 12 M Eur, the water consumption was reduced by 48 M m^3 and the waste was reduced by 1.4 M tons over a period of 10 years, which allows for the provision of food to 120 630 people. Finally, it is verified that the water footprint associated with food losses and waste is reduced by 21 M m^3.

An expansion of this model could be developed to involve the interconnections between industries that utilize by-products, by exploring industrial symbioses. Those potential industries should be incorporated as buyers and the network design could be enhanced considering those secondary flows. To obtain more accurate results related to water consumption, the water footprint of different potato varieties should be further explored, as well as consider the specific water requirements and waste levels for each supplier. Additional data related to individual suppliers' locations could influence transportation costs and associated water consumption.

References

Agnusdei, G. P., Coluccia, B., Pacifico, A. M., & Miglietta, P. P. (2022). Towards circular economy in the agrifood sector: Water footprint assessment of food loss in the italian fruit and vegetable supply chains. *Ecological Indicators*, *137*. https://doi.org/10.1016/j.ecolind.2022.108781

Allaoui, H., Guo, Y., Choudhary, A., & Bloemhof, J. (2018). Sustainable agro-food supply chain design using two-stage hybrid multi-objective decision-making approach. *Computers and Operations Research*, *89*, 369–384. https://doi.org/10.1016/j.cor.2016.10.012

Chartres, C., & Sood, A. (2013). The water for food paradox. *Aquatic Procedia*, *1*, 3–19. https://doi.org/10.1016/j.aqpro.2013.07.002

Deng, Y., Chen, X., Adam, N. G. S., & Xu, J. (2022). A multi-objective optimization approach for clean treatment of food waste from an economic-environmental-social perspective: A case study from china. *Journal of Cleaner Production*, *357*. https://doi.org/10.1016/j.jclepro.2022.131559

FAO. (2020). https://www.fao.org/aquastat/en/

Hess, T. M., Lennard, A. T., & Daccache, A. (2015). Comparing local and global water scarcity information in determining the water scarcity footprint of potato cultivation in great britain. *Journal of Cleaner Production*, *87*, 666–674. https://doi.org/10.1016/j.jclepro.2014.10.075

Huijbregts, M. A., Steinmann, Z. J., Elshout, P. M., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., & van Zelm, R. (2017). Recipe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. *International Journal of Life Cycle Assessment*, *22*, 138–147. https://doi.org/10.1007/s11367-016-1246-y

Krishnan, R., Arshinder, K., & Agarwal, R. (2022). Robust optimization of sustainable food supply chain network considering food waste valorization and supply uncertainty. *Computers and Industrial Engineering*, *171*. https://doi.org/10.1016/j.cie.2022.108499

Marston, L. T., Read, Q. D., Brown, S. P., & Muth, M. K. (2021). Reducing water scarcity by reducing food loss and waste. *Frontiers in Sustainable Food Systems*, *5*. https://doi.org/10.3389/fsufs.2021.651476

Motevalli-Taher, F., Paydar, M. M., & Emami, S. (2020). Wheat sustainable supply chain network design with forecasted demand by simulation. *Computers and Electronics in Agriculture*, *178*. https://doi.org/10.1016/j.compag.2020.105763

Rezaei, M. (2017). *Feature articles food loss and waste in the food supply chain*. http://theplate.nationalgeographic.com/2016/01/22/kenyan-farmers--ght-food-loss-by-drying-selling-mangoes/.

Sharifi, E., Fang, L., & Amin, S. H. (2023). A novel two-stage multi-objective optimization model for sustainable soybean supply chain design under uncertainty. *Sustainable Production and Consumption*, *40*, 297–317. https://doi.org/10.1016/j.spc.2023.07.006

Tang, X., He, Y., Qi, P., Chang, Z., Jiang, M., & Dai, Z. (2021). A new multi-objective optimization model of water resources considering fairness and water shortage risk. *Water (Switzerland)*, *13*. https://doi.org/10.3390/w13192648

UN. (2022). Water and sanitation - united nations sustainable development. https://www.un.org/sustainabledevelopment/water-and-sanitation/