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

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Industrial Engineering and Management

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Declaration

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

Declaração

Declaro que o presente documento é um trabalho original da minha autoria e que cumpre todos os requisitos do Código de Conduta e Boas Práticas da Universidade de Lisboa.

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Resumo

As crescentes preocupações de sustentabilidade levaram empresas a procurar oferecer opções mais sustentáveis. A agricultura representa uma percentagem significativa do consumo de água mundial e o desperdício alimentar intensifica esse consumo. Este trabalho apresenta uma ferramenta de apoio à decisão baseada num modelo multi-objetivo de programação linear para o planeamento das cadeias de abastecimento, com foco no desperdício alimentar e consumo de água. Para lidar com a incerteza na procura, foi utilizada a programação estocástica. O modelo foi validado utilizando um caso de estudo do setor agro-alimentar e a nova cadeia de abastecimento proposta é analisada utilizando o método ϵ-constraint.

O modelo proposto considera a cadeia na sua globalidade, desde o cultivo até aos mercados, considerando o stress hídrico e o consumo de água de cada região. As decisões incluem a seleção de fornecedores, planeamento da produção, a definição do tipo de produto, o local das instalações e o possível investimento em tecnologias que permitam a redução das perdas alimentares. As funções objetivo são a minimização do impacto ambiental associado à utilização de recurso hídrios usando uma abordagem de avaliação do ciclo de vida (LCA), minimização do desperdício alimentar e partes não usadas na produção final e maximização do desempenho económico.

Os resultados sugerem que o desperdício alimentar é mais crítico na fase de consumo final, representando 57% da água perdida devido ao desperdício ao longo da cadeia. Redefinindo produtos e fornecedores, é possível reduzir o consumo de água em 28% e o desperdício total em 15%.

Palavras-chave: escassez de água, desperdício alimentar, planeamento da cadeia de abastecimento, sdg6, multi-objetivo, cadeias de abastecimento sustentáveis

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 analyzed 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 15%, respectively.

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

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Acronyms

FCI	Fixed Capital Investment
FP	Final Products
FSC	Food Supply Chain
LCIA	Life Cycle Impact Assessment
NPV	Net Present Value
RM	Raw Materials
SC	Supply Chain
SDGs	Sustainable Development Goals
UN	United Nations
WCP	Water Consumption Potential
WUE	Water-use Efficiency

Chapter 1

Introduction

1.1 Problem Contextualization and Motivation

Due to the rapid and strong 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 increasing consumer demand is the scarcity of resources on the planet (Chartres and Sood, 2013).

Recently, the Earth's population reached 8 billion, highlighting the unequal distribution of resources and resulting in inadequate living conditions for a significant portion of the population. Population growth drives the expansion of urban areas, which, in turn, escalates the demand for resources in sectors such as agriculture, industry, and energy. One of the primary concerns is the 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. Regarding water availability, it is expected that by 2050 there will be enough world's water supplies for the global consumption of the expected population, however, the major problem is the poor distribution of it due to overconsumption and climate changes, especially in developing countries, which will lead to inaccessibility of resources for all the estimated 9 billion people. The intensification of water scarcity in regions already grappling with this issue is exacerbated by climate change. During the last century, water consumption has surged sixfold and continues to rise at a steady pace of 1% annually (UN, 2020). One of the basic needs for human life is access to safe water and sanitation to promote hygiene habits, essential for health and well-being. Some progress is being made towards providing access to this resource to the entire population, however, even so, the effort has to be intensified, otherwise, billions of people will continue to lack access to water by 2030 (UN, 2022b).

To respond to the sustainability problems that society has faced in recent decades, in September 2015, the 193 member states of the United Nations (UN) adopted the 17 Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development (UN, 2022a). These goals were defined to guide society's actions during the next 15 years (from 2015 until 2030) and to consider everyone who lives in the world, respecting the planet and the ecosystems. Figure 1.1 represents the 17 goals established. Due to the urgency of this topic, some progress has already been achieved (from 2015 until 2020): the percentage of the population using safely managed drinking water increased from 70 to 74 and the percentage of the population with safely managed sanitation increased from 47 to 54. This progress is positive and contributes to the 6th goal represented in figure 1.1, however, the rates of progress have to quadruple to achieve the goals set for 2030, which demonstrates the urgency of accelerating changes in course (UN, 2022b).

Figure 1.1: Sustainable Development Goals
Source: UN, 2022a

Beyond enhancing the use and management of water resources, it is necessary to extend this management to other sectors that are intrinsically linked 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 (Li et al., 2023). Figure 1.2 shows the percentage of freshwater used in each sector where it is observed that most of the water is applied to agriculture. The food demand is also projected to increase by over 60% compared to the requirements of 2005-2007 (Chartres and Sood, 2013), which will intensify the need to act in this sector.

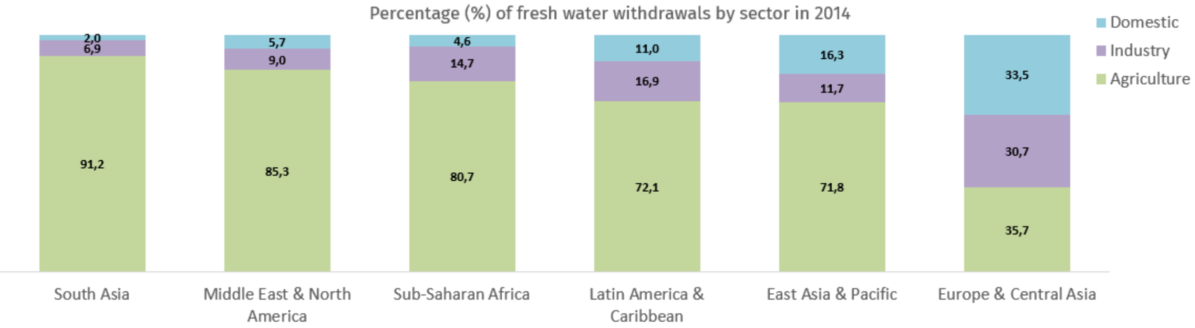

Figure 1.2: Freshwater withdrawals by sector (in percentage). Adapted from Khokhar, 2014.

Moreover, it is still necessary to deal with problems associated with the mismanagement of resources in the past. Years of improper use, inadequate management, excessive pumping of groundwater, and pollution of freshwater sources have worsened the problem of water scarcity. Nowadays, the problem is intensified due to the under-investment in the efficient management of water resources and also due to the lack of cooperation and organization between neighbouring countries, which leads to poor management of transboundary waters (UN, 2022b).

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. These losses occur at various stages, including on-farm, during transportation, storage, wholesale, and processing, depending on each industry. During the past years, since 2016, these values have remained relatively stable, which suggests that the companies have to rethink their strategies, to achieve better results. Furthermore, it is estimated that in 2019, approximately 17% of the total food available for final consumption was wasted near the retail levels. This means that a significant portion of food is discarded or goes unused, contributing to the overall problem of food waste. Efforts to reduce food loss and waste throughout the supply chain are crucial to address the challenges associated with feeding a growing global population and ensuring food security for all (UN, 2022b).

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 in regions experiencing water stress, food waste and loss can exacerbate water scarcity and contribute to water shortages. In addition, producing food that goes to waste also requires energy, fertilizers, and other resources that contribute to environmental degradation and can further impact water resources. Reducing food waste and loss improves water management practices, which can ultimately help alleviate water stress. In Figure 1.3, which shows the level of water scarcity and food loss and waste over the world, it is evident that some regions with high water scarcity levels also tend to have higher rates of food loss. By implementing effective conservation and management practices for both water and food resources in these regions, it is possible to achieve more efficient and sustainable use of these resources. 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).

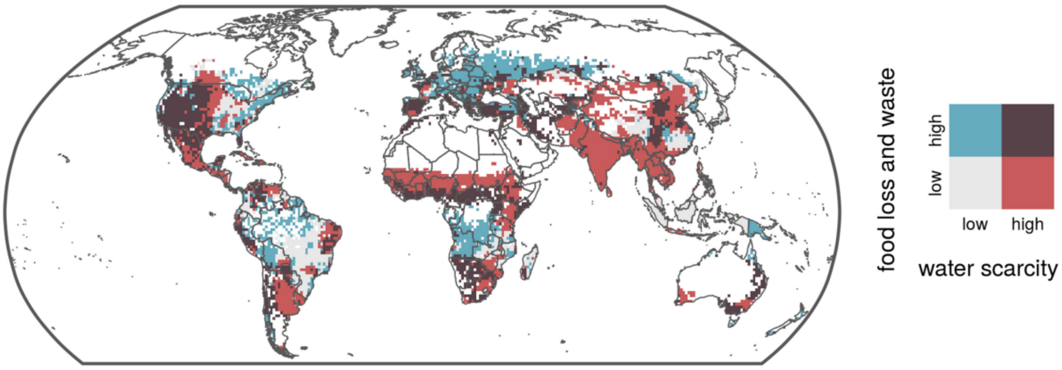

Figure 1.3: Representation of the regions over the world, according to the level of water scarcity and food losses in the predominant crops in each area.
Source: Marston et al., 2021

1.2 Objectives

The objective of this work is to contribute to solutions for the problem of water scarcity and food loss and waste, through the development of a generic optimization model for the strategic level of a food supply chain (FSC) that can be applied across various sectors within the food industry. The model is centered on devising management strategies that aim to reduce food waste and loss, while also minimizing water consumption and considering the water stress level of regions where operations occur. All the while, the model ensures the economic performance of the companies is maintained. The approach consists of eight distinct steps, outlined in Figure 1.4.

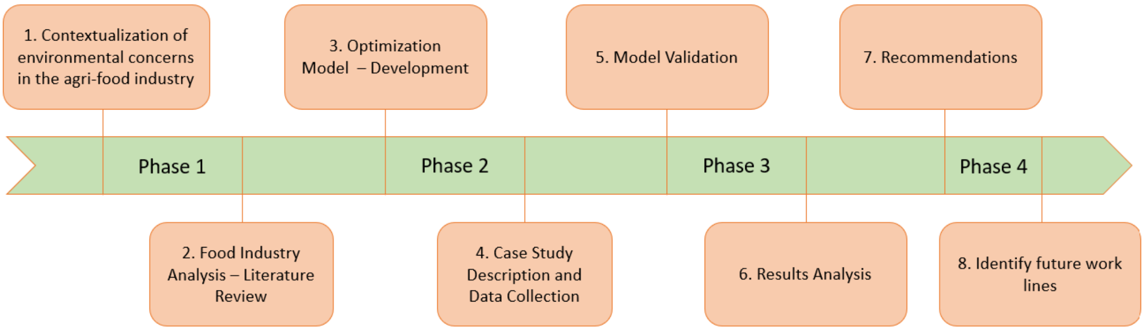

Figure 1.4: Research Framework.

By creating a general model applied to a specific case study, the hope is to provide a framework that can be tailored to meet the unique needs of FSCs. It is worth noting that every company operating within the food industry is unique, and as such, adaptations may be necessary when applying this specific model. This way, considering the specific parameters of water consumption, waste and losses, and the different phases of the operations of a FSC, it is possible to apply this framework and identify strategies that pave the way to more sustainable operations. By implementing a model that intertwines water consumption and food waste and loss, companies can better assess the influence on water consumption when reducing food waste and loss, and vice versa.

As described in figure 1.4, this study comprises the following steps:

- **Contextualization of environmental concerns in the agri-food industry:** The objective of this step is to understand the connection between the concepts of water scarcity and food waste and to highlight their importance. This overview is essential for understanding the challenges faced by the food sector nowadays, which drove the present study. By examining the interrelationship between these two concerns, the aim is to bring to light the complex interaction between water resources and food production and emphasize the need for sustainable practices to address these challenges.

- **Food Industry Analysis - Literature Review:** The literature review presents an overview of the latest research conducted focused on water resources and food loss and waste, with a focus on existing optimization models. The goal is to identify research gaps, and the most adequate methodology and determine the direction for the dissertation. The objective is to explore the existence of research that intertwines the specified topics and to comprehend how they are examined in the field of supply chain design and planning.

- **Optimization Model Development:** Before developing the model, it is necessary to define the problem and its specific requirements. After that, the equations, sets, parameters, decision variables, constraints and objective functions used in the model can be defined.
- **Case Study Description and Data Collection:** The optimization model applied to a real case study requires a large amount of data, in this case, related to the water consumption of different entities, the percentage of raw materials that are used and the water stress level of each region. Therefore, the data needs to be carefully analyzed and processed. This involves a significant amount of data treatment, as some of the required data may need to be estimated. Proper data analysis and treatment are essential for ensuring the accuracy and reliability of the results.
- **Model Validation:** This step involves applying the model developed to the data collected. The model is tested under different scenarios, considering uncertainties such as changes in demand. Moreover, the model was tested considering single objective cases, for each objective defined. The objective is to identify the most significant changes in the model's output when testing with different objective functions, which in this case reflect the different goals of reduced water consumption and reduced food waste and loss. By testing the model under multiple scenarios, it is possible to ensure that it can accurately and effectively address the identified issues. The model is also modified to simulate the current situation (As-Is), which will then be compared with the proposed solution (To-Be).
- **Results Analysis:** The ultimate objective is to draw meaningful conclusions from the results obtained when applying the model to a real case. Thus, it is verified that by suggesting new suppliers, different raw materials varieties with different water consumption, different factories that are associated with higher water-use efficiency, producing different final products aiming to reduce waste and losses and minimize the water usage in areas suffering from water stress, it is possible to achieve improved results regarding the sustainability concerns pointed.
- **Recommendations:** Finally, based on the proposed solutions and insights obtained from the optimization model, the goal is to formulate recommendations and suggest possible changes that should be implemented in the SC under analysis.
- **Identify future work lines:** An additional aim is to identify areas for future research that can provide further insights into the identified problem. After analyzing the results generated by the model, specific aspects may emerge as candidates for deeper investigation in future research.

1.3 Thesis Outline

This dissertation is organized into six main chapters:

- Chapter 1: Introduction - This chapter provides an overview of the topic of concern and situates it within a broader context. It also identifies the motivation behind the study and its relevance. The chapter presents the main objectives of the study, which serve as a road map for the analysis.
- Chapter 2: State of Art - The state of art chapter provides an overview of the theoretical concepts that will be necessary to understand the study's context. It also aims to identify the existing optimization models in the field of water consumption and food waste, to identify gaps in the literature, to summarise existing knowledge on the topic, and to guide the research's methodological approach.
- Chapter 3: Methodology - This chapter presents the general problem under study and its specifications. It outlines the mathematical formulation developed and the methodology followed.
- Chapter 4: Case Study Description - This chapter presents the case study description, and the data treatment process and outlines the scenarios under study. It provides an overview of the data sources used and describes the methods used to build the data.
- Chapter 5: Case Study Results Analysis - In this chapter, the results obtained using the mathematical model are analyzed and explored according to different scenarios and cases and a sensitivity analysis is performed. After that, the solutions obtained are presented and the most relevant issues are identified. By applying a multi-objective analysis, a new network design is proposed.
- Chapter 6: Conclusions - This chapter summarizes the main findings of the dissertation and discusses the limitations. It highlights the key insights generated by the analysis and suggests possible directions for future research in this field.

Chapter 2

State of Art

In a planet where most of the surface is covered by water, it would not be expected that less than 3% of this water corresponds to freshwater. Moreover, more than 68% of the freshwater available is stored in ice caps and glaciers. At the same time, around 30% is groundwater, and only 0.3% corresponds to water on the surface, such as rivers and lakes (Covitt et al., 2022). These numbers show that fresh water is a scarce resource on our planet. In addition, the available water resources are not equally distributed among the different regions of the globe. Thus, some parts are experiencing water stress, meaning the demand for freshwater exceeds the amount sustainably available in a given area (Vanham et al., 2021). It is considered that a specific part is experiencing water stress when the ratio of water withdrawals compared to the total availability is higher than 25%. As the percentage grows, the water stress can range from low to critical, increasing water pressure in that area and consequential negative impacts. Water stress can lead to devastating consequences from an environmental, economic, and social point of view (Nations, 2022).

The average level of water stress in the world is 18.6%. Despite remaining below 25%, North Africa and West Asia are already at a critical level, and the values have increased by around 13% since 2015. To reduce these values, efforts must be made to improve water use efficiency, mainly in agriculture and industry. From 2015 to 2019, water use efficiency in industry increased by 12%, but these values remain low in agriculture. This activity consumes the most water, so minor improvements can be significant (Nations, 2022).

The agri-food sector has been highly affected by water scarcity and food waste policies that force entities to establish clear water-related regulations. It is essential to encourage farmers to adopt better water and soil management practices in their activities, and policies that lead to excessive water consumption should be revised. Companies are focused on finding ways to cross issues related to respect for the environment and the resources available (Esposito et al., 2020). Note that food waste occurs in supply chains from its initial stage, namely farmers, to final consumers, passing through all the intermediate processes (manufacturing, transportation, storage, etc.), involving different companies and entities focused on finding solutions for the issues pointed.

The rapid development of the economy and society leads to high quantities of food waste and the consumption patterns have contributed to an increase in the unsustainable management of food (Deng et al., 2022). Food waste is highly connected with consumer behaviour and companies should make an extra effort to encourage and educate consumers to make more sustainable purchases. The ”green products” are usually more expensive than the same product that is not produced in an environmentally friendly way, and the consumers are not willing to pay the additional costs when they are not well informed (Taghikhah et al., 2019). One highly effective way to minimize food waste is by transforming it into a valuable resource. Instead of discarding unused food, there are methods to harness its potential to create new products or utilize it in various beneficial ways (Sridhar et al., 2021).

During the last few years, more researchers have been focused on developing optimization tools that allow an overview of the whole supply chain (Deng et al., 2022) focused on achieving their economic, environmental and social objectives. Nowadays, the supply chain design is even more complex due to the high dimension of flows with different sources and destinies (Yadav et al., 2022). By implementing models that consider the whole SC, it is possible to evaluate other metrics such as water and land use (Lu et al., 2012) as well as gas emissions while maximizing the net annual return, for example (Li et al., 2020).

2.1 The impact of food waste on water resources available

The concepts of water scarcity and food waste are closely interconnected, such that reducing one can result in a reduction of the other (Marston et al., 2021). Reducing society’s water footprint is an effective way to deal with water scarcity. The water footprint related to the food sector can be reduced by increasing water-use efficiency (quantity of water used for a particular activity), reducing food waste and loss, which also represent a significant portion of the water footprint of the food industry, or by choosing more sustainable products that lead to lower levels of waste (Mekonnen and Fulton, 2018).

2.1.1 Water footprint of agri-food

Water footprint has been proposed by Hoekstra, based on previous concepts studied by Allan, and it has been one of the measures used to study the impact of products and activities on water resources. The term considers the total amount of water used in a specific location or by an entity for a particular activity and includes both physical and virtual water (Hoekstra and Hung, 2002).

Physical water refers to the water consumed for a specific activity and considers the water directly used for irrigation, industry, or domestic use. Conversely, virtual water is an indirect measure representing water used over the entire supply chain for a specific product, including the water used in the different processes. Broadly, virtual water considers all the not directly visible water and is included in product trading (Lee et al., 2023). Both concepts are relevant when assessing water usage along the supply chains.

When analyzing water footprint, three different concepts are essential to consider. Blue water represents the water consumption of surface water and groundwater, green water accounts for the consumption of rainwater that is stored in the soil during the growth of crops, and finally, grey water represents the water needed to dilute a polluted water portion (Kou et al., 2023).

2.1.2 Food loss and waste in supply chain

Food waste and loss are related to decreased 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 and storage, and near the final consumers (Rezaei, 2017).

The two concepts are similar; however, there are differences between food waste and loss. 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 that was produced for human consumption. These factors include system malfunctions, inadequate storage, improper food handling practices, inadequate packaging, and inefficient cooling systems. Food waste, conversely, pertains to food discarded or removed from the supply chain despite being edible for human consumption. Food waste can occur due to poor stock management or neglect, leading to expired food (Rezaei, 2017). The United States Department of Agriculture considers food waste a sub-component of food loss (Ishangulyyev et al., 2019). The possible causes for food loss and waste in each stage of the supply chain (Ishangulyyev et al., 2019) are pointed out in table 2.1.

Table 2.1: Possible causes of food loss and waste and possible actions to avoid it.

Source	Possible Causes	How to avoid
Production/Agriculture	- Over Production (Gustavsson et al., 2011) - Harvesting methods: manual or mechanic (Beretta et al., 2013) - Harvesting timing (Gustavsson et al., 2011) - Quality Standards (appearance) (Beretta et al., 2013)	In developed countries: cooperation among farmers to reduce overproduction In developing countries: educate farmers and organize them in small groups (Gustavsson et al., 2011)
Handling and Storage	- Storage (Ishangulyyev et al., 2019) - Transportation (Ishangulyyev et al., 2019) - Spillage and Degradation during handling (Ishangulyyev et al., 2019)	Train supply chain operators to handle food safely and increase hygienic practices (Gustavsson et al., 2011)
Processing	- Unavoidable losses - Contamination in production lines - Inefficiencies in production lines (Ishangulyyev et al., 2019)	Introduce 'sub-standard' products in the markets that are still eatable. In addition, identify ways to use peels and trimmings (Gustavsson et al., 2011)
Distribution	- Inefficient Packaging - Inadequate transport conditions - Road conditions and distribution vehicles used (Ishangulyyev et al., 2019)	Improve transportation vehicle and guide the workers to prepare the products (Ishangulyyev et al., 2019)
Consumption	- Over cooking - Individual attitude - Storage in household (Ishangulyyev et al., 2019)	Reduce portions and provide education about food loss and waste. Moreover, supermarket management to forecast customer demand is important (Ishangulyyev et al., 2019)

Overall, it is considered that food loss occurs in the first stages of the supply chain, near the farmers and processing. In contrast, food waste occurs mainly but not exclusively at the retailer level as presented in figure 2.1.

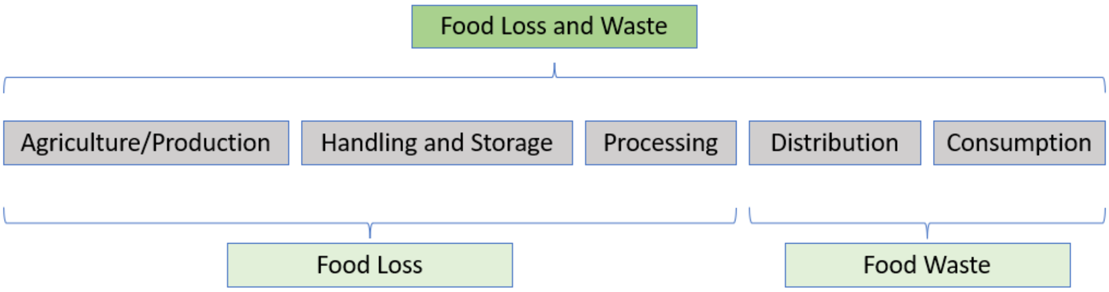

Figure 2.1: General food loss and food waste definitions.
(Ishangulyyev et al., 2019)

It is also relevant to note that the distribution of food waste and losses does not occur similarly in different regions. It is estimated by the World Institute of Resources that considering the food waste and loss over the world, 44% corresponds to developing countries and 56% corresponds to developed countries (Lipinski et al., 2013). While developed countries tend to exhibit higher rates of food waste, developing countries often face significant food loss due to limited resources to address the issue effectively. Figure 2.2 represents the distribution of food loss and waste in different supply chain stages.

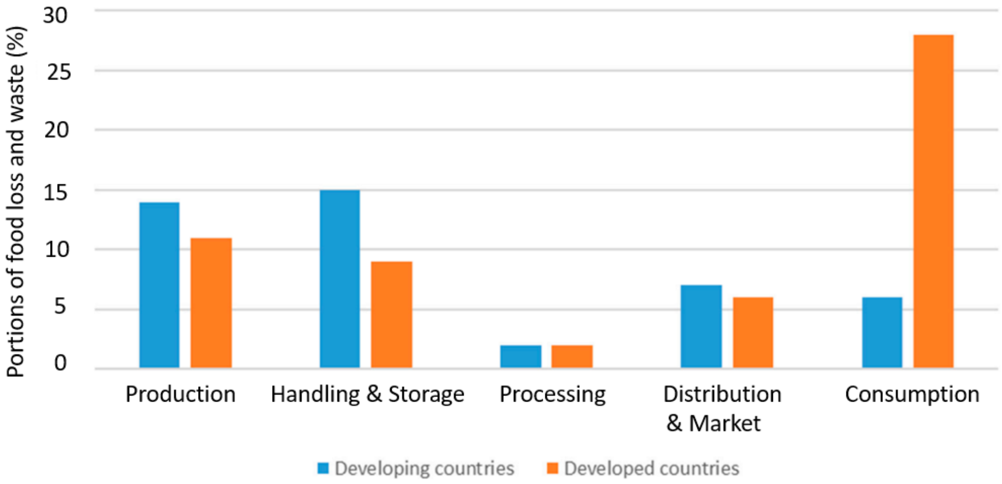

Figure 2.2: General food loss and food waste in different stages of the SC.
Source:Ishangulyyev et al., 2019

When considering the percentages, it becomes evident that distinct approaches should be outlined to address and reduce food loss and waste in each region.

In the food sector, it has been assessed that roots and tubers, followed by fruits and vegetables, represent higher values of food loss and waste. Therefore, it is crucial to prioritize efforts to address the issues related to these categories (Flanagan et al., 2019).

Food waste and loss are also categorized as avoidable or unavoidable. Avoidable waste mainly occurs in households, while unavoidable waste accounts for portions that are not edible, such as peels and seeds. Studies on this topic show that unavoidable waste can be converted into valuable and different components (Joglekar et al., 2019). Potatoes are the fourth most widely consumed crop globally, and discarded peels often end up as waste. However, recent studies have revealed the tremendous potential of these components, as shown in figure 2.3 (Pathak et al., 2018). Factories dedicated to potato production can introduce techniques to treat these components or sell them to other industries as a by-product, benefiting from industrial symbiosis (Escanciano et al., 2023). In the specific case of the potato industry, the most relevant by-products are peels, discarded potatoes (low quality or old), potato leaves, and starch processing wastewater (Escanciano et al., 2023).

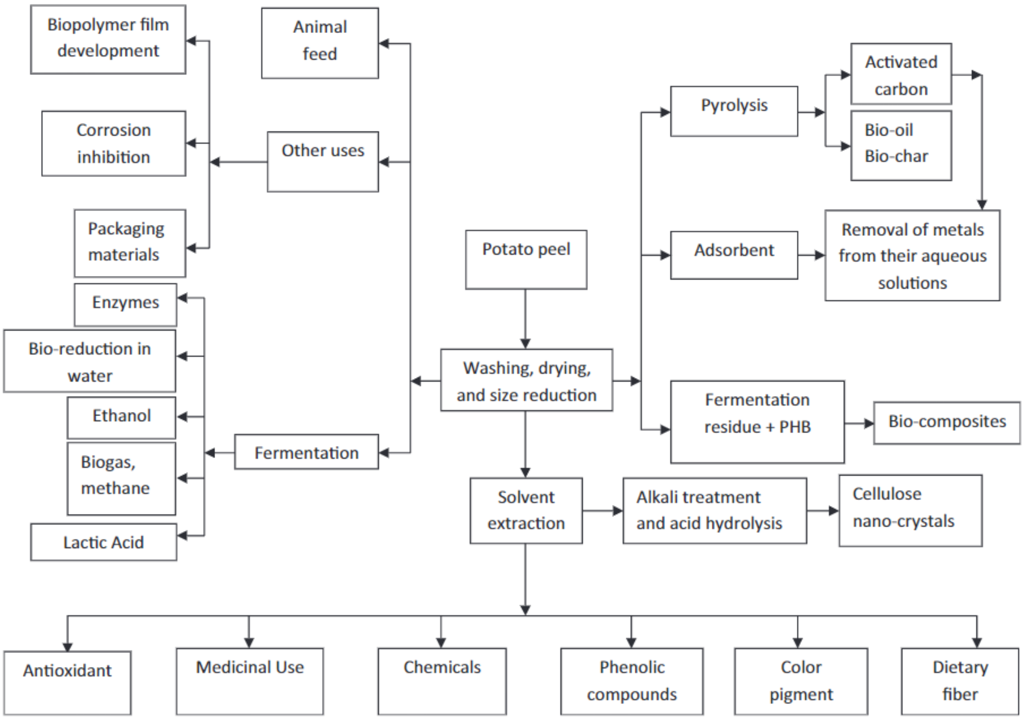

Figure 2.3: Potato Peels utilization.
Source:Pathak et al., 2018

2.1.3 Mitigating Water Scarcity through the Minimization of Food Waste and Loss

Around one-quarter of the food produced is lost along the supply chain. Moreover, the production of this food that is lost or wasted represents around 24% of the freshwater resources used for crop production and 23% of the global cropland area and fertilizers, in the case of the agri-food supply chain (Kummu et al., 2012).

Furthermore, due to variations in losses and waste across different geographic regions, projections indicate that adopting the lowest loss and waste rates observed in South and Southeast Asia could potentially lead to a 50% reduction in losses globally. This, in turn, could provide additional food for one billion people. Emphasizing reducing food waste and loss is directly linked to optimizing resource utilization, particularly the freshwater consumed throughout the supply chain (Kummu et al., 2012).

Approximately 58 litres of water per capita per day of food waste are wasted. This value reaches 118 litres for high-income countries, while for low-income countries, the value is reduced to 12 litres (Chen et al., 2020). Food loss and waste vary per region, primarily due to different diets and consumption patterns. Thus, if all the inhabitants had the same diet as in North America, the percentage of all freshwater available that would be used inefficiently would be around 20% (Marston et al., 2021).

2.2 Supply chain management practices to reduce food waste and water losses

To halve per capita global food waste and losses along production and supply chains, corresponding to target 12.2 of the sustainable development goals (UN, 2023), a set of coordinated solutions is needed. Reducing food and water waste is recognized as a potential solution, but its practical implementation is complex due to cultural, regulatory, and economic factors. To achieve the desired levels of efficiency at each stage of the supply chain, it is necessary to understand the impacts of specific policy interventions better and develop geographically accurate tracking approaches to better control the flows of food and resources along the supply chain. For this, additional research is needed to reduce uncertainty and consider improved data collection, integrated assessment of policies and measures to combat water consumption and reduce the environmental impact associated with food loss and waste (Marston et al., 2021).

Previous studies in the United States context concluded that shifting to different diets (e.g. from meat-based to plant-based), can be effective in reducing the water footprint of the food sector, however, it can be also unrealistic due to cultural differences. On the other hand, the reduction of food waste and losses has a higher potential to reduce water footprint. Instead, actions should be defined to minimize waste (Mekonnen and Fulton, 2018) and reduce the water footprint of agri-food supply chains by improving water-use efficiency.

Another study emphasizes mapping water footprints and virtual water usage to establish appropriate trade policies and enhance supply chain management (Miglietta et al., 2022). However, a research gap still exists in identifying methods to select crop locations, particularly to address high-level issues like water scarcity in specific regions.

Progress in water footprint assessment research should be improved to define policies and strategies to drive production processes. In agri-food supply chains, redesigning the networks can minimize waste and optimize water usage. By considering circular economy practices, it is possible to create more sustainable production cycles by closing the raw materials and resources loop. Thus, continuous efforts are needed to transform research results into actionable policies that drive the agricultural and food sectors toward a more circular and sustainable future (Agnusdei et al., 2022). The main challenges faced are devising management mechanisms for supply chains that consider translating water footprint data into tangible actions (Hoekstra et al., 2019).

Moreover, other authors also emphasize the importance of better-managing wastewater. When developing SC networks, creating decision-making tools that consider resource scarcity and aim to minimize environmental impact based on the area's economic power becomes crucial. One practical approach to optimize wastewater treatment in industrial estates is industrial symbiosis. This method involves reusing organic matter present in food wastewater as, for example, an external carbon source from wastewater treatment plants. Biodegradable organic matter, like food waste, is abundant in industrial wastewater and can be used for different activities. By implementing the industrial symbiosis model, focused on wastewater treatment systems within industrial parks, significant cost savings, and environmental benefits have been achieved while reducing waste (Ledari et al., 2023).

2.3 Tools for reducing food waste and water loss in supply chain management: a comparative review analysis

This subsection delves into mathematical optimization models for supply chain design and planning. It investigates studies addressing the issues of water scarcity and food waste within existing supply chains. These studies employ LCIA (Life Cycle Impact Assessment) techniques, which are important for retrieving data that feed into the optimization models.

Data regarding water use

Supply chain network design involves strategic and long-term decision-making, often called the facility location problem. This analysis enables the determination of optimal locations for entities or facilities based on economic, environmental, or social objectives (Mohammed et al., 2023).

In the scope of single and multiple objective problems, future directions lie in focusing on multi-objective solutions, embracing novel methodologies, and prioritizing green, sustainable, and environmentally friendly objectives. By considering the simultaneous optimization of multiple goals, exploring innovative approaches, and aligning with environmental objectives, supply chains can be more sustainable and efficient in the future (Govindan et al., 2015) while intending to keep the economic performance.

In particular, the literature reveals insufficient research on supply chain network design in the food sector (Mohammed et al., 2023). The research on environmental impact assessment in supply chain network design involves various methodologies, with Life-Cycle Assessment (LCA) and partial assessment of specific ecological factors being prominent options. LCA is widely recognized as a framework for evaluating the environmental impacts of a product through its entire lifecycle, and the ReCiPe method is one of the methodologies available that is better developed and widely accepted in the European context. Moreover, note that the European Commission recommends PEF (Product Environmental Footprint) to help companies calculate their environmental performance based on reliable data (Environment, 2021). Despite these advancements, the challenge lies in defining a standard methodology. By applying environmental impact assessment and optimization models, decision-makers can make informed long-term decisions and select an appropriate supply chain network design considering specific environmental factors defined (Seuring, 2013) and the targets identified.

In the literature, it is stated that LC-based methodologies can be a valuable tool to assess the water footprint or different key factors such as land use or carbon emissions (Boulay et al., 2013). By having data available about the water footprint of a certain activity, it is possible to quantify crops' water footprint in different regions. Those results allow to define guidelines to achieve more sustainable practices. A study within the potato production sector demonstrates the value of having detailed information about water usage, specifically categorizing it into blue, green, and grey water. A comparative analysis of the proportions of each water type used enables insights that can guide farmers in enhancing their irrigation efficiency and in devising strategies to reduce the risk of groundwater pollution (Rodriguez et al., 2015). The same study also states that the volume of water used also depends on land use efficiency. When assessing the water footprint of a specific entity, the tons produced per unit of area are relevant to be considered (Rodriguez et al., 2015). Thus, that can influence the quantity of water each farmer uses, leading to different water footprints associated with a specific product in a particular region.

Another study in the potato sector in Great Britain emphasizes the importance of measuring water consumption per region but also considers a global map of water scarcity (Hess et al., 2015). By analyzing crop production from this point of view, it is possible to establish "hotspots" of water-related risk for potato production.

By incorporating water stress characterization factors, decision-makers can establish a connection between global consumption and water scarcity and better analyze the local and regional impact (Ridoutt and Pfister, 2010). The few studies that consider water stress when assessing water environmental impact of a specific activity (Hess et al., 2015, Ridoutt and Pfister, 2010) use a logistic function based on the withdrawal-to-availability ratio (Alcamo et al., 2003) to characterize the level of water stress as "low" (water stress index lower than 0.1), "moderate" (water stress index between 0.1 and 0.5) or "severe" (water stress index higher than 0.5) (Pfister et al., 2009). After identifying the water stress index of each region, the new proposal intends to obtain a stress-weighted footprint by multiplying the water footprint by a characterization factor related to the water stress index (Ridoutt and Pfister, 2010) as represented in figure 2.4.

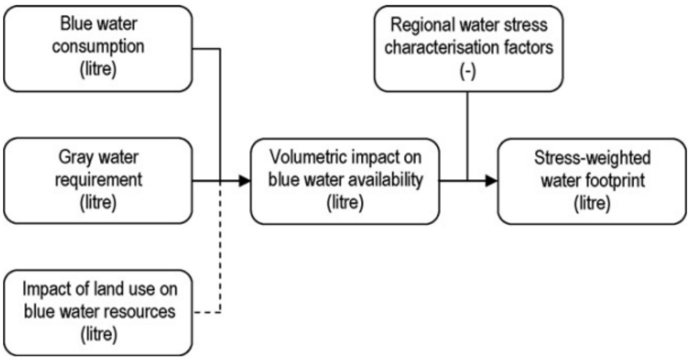

Figure 2.4: Method to calculate product water footprints by considering the water stress characterization factor.

Source:Ridoutt and Pfister, 2010

Optimization Models

Upon examining the studies outlined in Table 2.2, it becomes evident that existing research has extensively explored the economic and social aspects of the triple bottom line of sustainability.

Table 2.2: Recent studies in the field of sustainable food SC.

Paper	Environmental Impact		Economic Impact	Objective Functions	Model	Uncertainty	Application	Water footprint of food waste
	Waste	Water						
Musavi and Bozorgi-Amiri, 2017	-	-	X	Min Transportation Cost Min CO_2 emissions Max product quality	MILP	-	Perishable food SC	-
Allaoui et al., 2018	-	X	X	Min total costs Min CO_2 emissions and water use Max jobs created	MILP	-	Agri-food SC	-
Bortolini et al., 2016	-	-	X	Min Operating Costs Min CO_2 emissions Min delivery time	MILP	-	Fruits and Vegetables SC	-
Motevalli-Taher et al., 2020	-	X	X	Min Costs Min water consumption Max job opportunity	MILP	Simulation	Wheat SC	-
Sharifi et al., 2023	-	X	X	Max total profit Min CO_2 emissions Max jobs created Max Sustainability	MILP	Stochastic	Soybean SC	-
Mogale et al., 2020	-	-	X	Max total costs Min CO_2 emissions	MINLP	-	Grain	-
Krishnan et al., 2022	X	-	X	Min Costs Min Greenhouse gases emission Max jobs created	MILP	Robust	Mango	-
Deng et al., 2022	-	-	X	Max Profits Min carbon emission Max jobs availability	MILP	trapezoidal fuzzy numbers	food waste systems	-
Tang et al., 2021	-	X	X	Max Economic Benefits Max fairness Min structural water shortage risk	NLP	-	Wusu City	-
Li et al., 2020	-	X	X	Max Economic Benefits Min gas emissions and water pollution Min water use	MINLP	fuzzy numbers	China	-
Bing et al., 2014	X	-	X	Min Transportation Cost Min Env. Impact	MILP	-	Plastic Waste	-
Current Work	X	X	X	Max NPV Min waste and loss Min water env. impact	MILP	Stochastic	Agri-food SC	X

Some optimization models primarily focus on minimizing costs (Allaoui et al., 2018, Musavi and Bozorgi-Amiri, 2017, Bortolini et al., 2016) or maximizing profit. However, there appears to be a gap in the literature regarding models that consider Net Present Value (NPV), which would allow long-term investments in technologies, for instance, focused on lowering food waste or lowering the quantities of water used. Those investments are crucial in enhancing water use efficiency, whether in factories or agricultural fields.

No paper simultaneously addresses food waste and water consumption, nor does it consider the water footprint from food waste in the decision-making process. Upon reviewing the data in table 2.2, it is clear that carbon emissions have been the environmental impact receiving the most attention. This is likely due to the extensive regulations surrounding carbon emissions. Those studies considered the emissions to establish facilities (suppliers, factories, and distribution centres), the emissions related to transportation between facilities and it is also considered the emissions related to warehousing and inventory handling (Sharifi et al., 2023, Mogale et al., 2020). Despite those studies not focused on water consumption, Sharifi et al., 2023 studied several uncertainties in different parameters, such as demand, selling price and buying price by using a stochastic approach.

The studies identified overlook the importance of considering water stress in individual countries or regions when assessing water use. It is crucial to account for the specific water availability and stress levels in different areas to better understand the environmental impact. Furthermore, in evaluating the environmental impact along the SC, the studies tend to neglect the significant issue of food loss and waste. By implementing optimization models that consider different product categories leading to varying amounts of waste, it becomes possible to trace and identify inefficiencies along the value stream more effectively (Yadav et al., 2022).

Of the articles identified, only five are 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 water is only considered for the supplier's selection while considering other social, environmental, and economic indexes. Aside from that, Allaoui et al., 2018 proposes 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. Other multi-objective non-linear programming models focus on balancing water and land resources for an agricultural system while maximizing economic performance, minimizing gas emissions and water pollution, and ensuring fair resource distribution (Li et al., 2020). Motevalli-Taher et al., 2020 presents a study 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.

Concerning waste, three 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, 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. That way, a possible approach would be to study the waste derived from each product or process used (Krishnan et al., 2022). Bortolini et al., 2016 study the distribution of fresh fruits and vegetables from suppliers to retailers by optimizing it, balancing the economic perspective, CO_2 emissions, and minimizing delivery time. By developing an optimization tool that allows an overview of the whole supply chain, it is possible to produce no waste since the quality is preserved during transportation.

A multi-objective model in sustainable reverse logistics aims to identify the most promising methods to separate plastic in a recycling system. The model considers different factors to identify better the techniques at a lower cost and a lower environmental impact. Although the purpose of the case is to reduce plastic waste, no objective function measures the efficiency of each method to reduce waste (Bing et al., 2014).

Another study evaluates the water footprint associated with fruit and vegetable losses, adopting a LCA perspective. Through the analysis of the water footprint for selected products, the research sheds light on the significant impact of food losses on water consumption, particularly in the case of products that require substantial amounts of water during cultivation. These losses contribute significantly to overall water wastage, and that emphasizes that effectively managing food loss can offer a valuable approach to mitigate the environmental impact of supply chains (Agnusdei et al., 2022).

Research gaps

Observing the literature review, the following research gaps were identified:

- Few studies contribute to solutions to reduce food waste and do not consider the levels of waste according to its product characteristics. Instead, the focus is on food waste valorization;
- When assessing the environmental impact the focus is mainly on gas emissions and few studies consider water consumption according to the level of water scarcity in each region;
- There is a lack of research to measure the environmental footprint of operations considering different product characteristics;
- Lastly, few studies consider demand uncertainty while designing FSC in the 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, 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. In parallel, the model should also account for the economic impact when designing a SC network. 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.

Chapter 3

Methodology

The next chapter defines the methodology followed to face water scarcity, food loss and waste concerns in a food supply chain. Section 3.1 will provide a general introduction to the problem, while section 3.2 will outline the mathematical formulation developed.

3.1 Problem Statement

This study aims to address the specific gaps identified in the existing literature. There is a scarcity of research focusing on sustainable optimization models that consider global water consumption and water-stressed regions. Furthermore, while there are some studies that identify points of loss and waste along supply chains, there is a noticeable gap when it comes to optimization models used to evaluate the impact of studying different products concerning waste levels.

Water scarcity is a global issue and the food sector is particularly vulnerable due to its reliance on water-intensive processes. After agriculture, industry is the second activity that consumes more water, especially in Europe and Central Asia. There is a dearth of research that comprehensively examines the impact of food losses on water consumption in the FSC. Furthermore, there is limited empirical support for the idea that optimizing supply chain processes effectively leads to a reduction in water consumption. Although this is one of the factors that can foster more sustainable water usage, achieving efficient operations requires considering regional water availability (water stress), potential technologies to curtail waste during the processing phase, and the production of various products that lead to different waste quantities and different by-products, among other factors. Most of the research tends to concentrate on specific sectors of the supply chain, rather than examining it in its entirety. This approach facilitates a deeper understanding of how decisions made at the supplier stage, for instance, can influence the reduction of the total water footprint for a particular product. Using optimization models, it is possible to quantify the amount of water that is wasted when food is lost or wasted in different scenarios. These models are a powerful tool for studying the trade-offs of using technologies to obtain by-products during the food production process, or for dealing with waste that cannot be used in the final products, while considering the water consumption. By using these models, companies can assess the impact of different strategies and make informed decisions.

To address this significant gap in the literature, the problem being analyzed aims to optimize a FSC by minimizing its environmental impact in terms of water and resource use while simultaneously maximizing economic performance.

A mathematical model is developed to guide the decision-making process regarding the supply chain network design. To validate the model, a case study in the deep-fried potato industry is applied, providing a practical application of the framework. This will enable to test the effectiveness of the model and refine it as necessary, as well as to gain valuable insights into the actual water usage and losses within the food supply chain.

The optimization model considers a generic network that establishes the exchanges between the different stages of the food supply chain, as illustrated in Figure 3.1. It represents the water utilized at various stages of the supply chain, encompassing both supplier operations and manufacturing processes within factories. Additionally, it is considered indirect water consumption in support activities like transportation and warehousing, which include packaging processes and refrigerated warehouses consumption. Furthermore, it is identified that losses occur mainly during crop development, post-harvesting procedures, and the manufacturing phases. Waste is only considered at the consumer level, specifically accounting for food wastage by customers at restaurants. This approach will enable to capture the complexity of the supply chain, while also providing a flexible and adaptable framework for analysis.

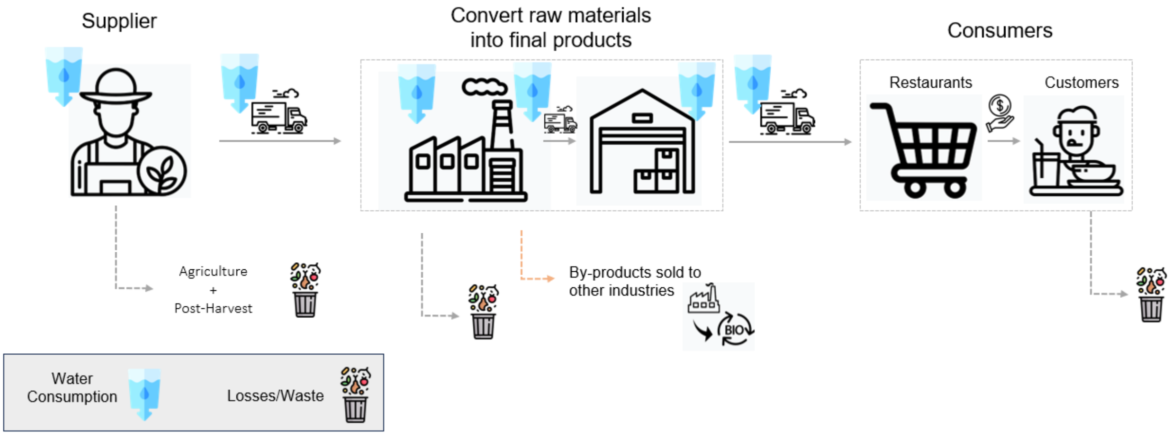

Figure 3.1: Generic supply chain for the food industry.

There are four relevant parameters in the model developed:

- Water stress per country;
- Water consumption per crops and per country;
- Water consumption of transportation, warehousing, packaging and production;
- Percentage of food losses and waste that occur, on average, at each stage of the SC and parts of products used or not for each type of final product;

Water Consumption

When assessing the water footprint of activities along the FSC, various LCIA 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, since it is one of the most commonly used for European research (Mota et al., 2018). More details about its choice are discussed in section 4.1. This method incorporates a specific indicator known as water consumption potential (WCP), which is expressed as the amount of water consumed (measured in cubic meters, m^3) per unit volume of water extracted (also measured in cubic meters, m^3) (Huijbregts et al., 2017).

Water stress is measured using an Index provided by ”Aquastat”, a global information system on water and agriculture developed by the Food and Agriculture Organization (FAO) of the United Nations (FAO, 2020). This database offers a percentage-based index to compare water availability and consumption in each country.

The objective function that measures the water environmental impact of operations considers the product of water consumption by the water stress level of each region where an activity occurs. That will influence the optimal locations chosen for the factories and select suppliers based on the locations of the crops. The water consumption also influences the quantities of products produced of each type, according to its water requirements. Different crops may have varying water consumption rates depending on the country or region, the crop itself, and even different varieties of the same crop can have distinct water requirements. This same logic applies to factories, where each one may consume different quantities of water depending on the technologies utilized.

Food Losses and Waste

The percentages of food loss or waste along the supply chain are discussed and presented in Section 4.1 and were recovered from an exhaustive study that analyzed these aspects in different types of FSC (Rezaei, 2017 and Gustavsson et al., 2011).

This study aims to maximize the parts of raw materials that are effectively used for the final products (FPs), however, there are always parts that cannot be used and there are two destinies possible: waste or use those by-products for other industries. In the industry under study, there are parts of the raw materials that 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 in the model.

The model considers a selection of different products that use the raw materials in different ways, influencing the quantities of raw materials needed to produce each final product. Thus, the model analyzes a selection of possible final products and determines the amount of each product that should be produced for each market in order to minimize food losses or waste. This will involve balancing supply and demand, as well as considering the potential for losses at each stage of the supply chain. By doing so, the model will provide insights into the most efficient way to operate the food supply chain while reducing water usage in areas suffering from water stress and maximizing economic profit.

Economic Performance

The economic performance is influenced by all the decisions previously identified. The costs are influenced by the supplier's location, the quantities of raw materials needed, the labour costs and the distances between entities, which influence transportation costs. The revenues are also influenced by the quantities of final products of each type sold and the by-products obtained during the processing phase.

Overall, given:

1. Possible 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 (EUR);
8. The selling price of by-products (EUR);
9. Transportation cost (per tons.km);
10. Market demand in each time period (year);
11. Bill of Materials (BOM) (tons);
12. Losses in Agriculture, Post-Harvest and during the processing phase (% compared to the quantity of products that arrive at the beginning of each stage);
13. Waste generated by consumers (% compared to the food that arrives to the markets);
14. Water-stress level of each location (suppliers, factories, warehouses) (%);
15. Amount of water used to produce the raw materials (m^3/ton);
16. Amount of water used to process one ton of frozen potatoes (water-use efficiency) in each factory (m^3/ton);
17. Water consumption for transportation $(m^3/ton.km)$ and warehousing;
18. Distances between entities (km);

The goal is to determine:

1. The quantity of raw materials cultivated based on the needs of the factories and considering the losses that occur;
2. The quantity of raw materials supplied for each factory;
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 according to strategic choices (suppliers, factories, final product characteristics);
6. The amount of food loss and waste that vary according to final products produced;
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 throughout the SC;
3. Maximize the network's Net Present Value (NPV);

3.2 Mathematical Formulation

In the subsequent section, the mathematical model is presented. The model is then applied to a representative case study in the fried potatoes industry for validation purposes.

Indices and related sets and subsets

i, j, io, id $\in$ I: Entities in different locations $I = i_{sup} \cup i_f \cup i_w \cup i_{mk}$

i_{sup}: Raw materials suppliers
i_f: Factories
i_w: Warehouses
i_{mk}: Markets

g $\in$ G: Processing technologies in factories - In the specific case study under analysis, this concept is exemplified by the various types of potato cuts employed in the production process, each of which yields distinct final products.

m, n $\in M = m_{rm} \cup m_{fp}$

m_{rm}: Raw materials
m_{fp}: Final products
m_{pot}: Final products made of potatoes
m_{asis}: Most common Final Products (Traditional)
m_{newpot}: New Final products made of potatoes
m_{newveg}: Final Products made of other vegetables
m_{new}: New Final Products considering both made of potatoes and made of vegetables

t $\in$ T: Time periods

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

For the description of each of these subsets, consider the following connections:

U^{sf}: Connection between suppliers and factories

U^{fw}: Connection between factories and warehouses

U^{wm}: Connection between warehouses and markets

V: Allowed product–entity relations $V = \{(m,i) : m \in M \wedge i \in I\}$

For the description of each of these subsets, consider the following connections:

V^{sup_rm}: Connection between suppliers and raw materials

V^{fac_rm}: Connection between factories and raw materials

V^{fac_fp}: Connection between factories and final products

$V^{w\text{-}fp}$: Connection between warehouses and final products

$V^{m\text{-}fp}$: Connection between markets and final products

H1: Product-technology pairs for production $H = \{(m,g) : m \in m_{fp} \wedge g \in G\}$

H2: Factories and technology pairs for production $V = \{(i,g) : i \in i_f \wedge g \in G\}$

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

For the description of each of these subsets, consider the following connections:

F^{OUTsup}: Flow of raw materials that leave supplier i and go to factory j

F^{INfrm}: Flow of raw materials that enter factory j and come from supplier i

F^{OUTffp}: Flow of final products that leaves factory i and goes to warehouse j

F^{INwfp}: Flow of final products that enter warehouse j and come from factory i

F^{OUTwfp}: Flow of final products that leave warehouse i and go to market j

F^{INmfp}: Flow of final products that enter market j and come from warehouse i

Parameters

Distances

$dsf_{i,j}$: Distance (km) between supplier i and factory j

$dfw_{i,j}$: Distance (km) between factory i and warehouse j

$dwm_{i,j}$: Distance (km) between warehouse i and market j

Entity Related

$sup\_cap\_max_{m,i}$: Maximum supply capacity for product m by supplier i

$fac\_cap\_max_i$: Maximum production capacity (tons) for each factory i

$FactoriesCapHour_i$: Capacity of factory i per hour (tons)

$MinFacCap$: Minimum factory capacity (tons)

$LaborCost_i$: Cost per hour for each employee in factory i

$Workers_i$: Number of employees in factory i

$dmd_{i,t}$: Aggregated demand for each market i in period t

$water\_stress_i$: Water stress level for each entity i

$FactoryCosts$: Percentage of revenues that is used to pay facility expenses

$wateruse_{m,i}$: Water-use efficiency of each factory i per final product m

Waste related parameters

$Losses\_Agri$: Losses in Agriculture

$Losses\_PostHarv$: Losses in Post-Harvest

$Water\_evaporated$: Percentage of water evaporated

$Used\_fp_m$: Percentage of raw materials that are used in the final product

$Used\_flakes_m$: Percentage of raw materials that are used in dehydrated potato flakes

$Used\_by_m$: Percentage of raw materials transformed into by-products and waste streams

$losses\_potatoe$: Percentage of raw materials considered waste

$starch\_recovered$: Percentage of raw materials that can be recovered when having technology installed to treat water

$Losses\_Market_{i,m}$: Percentage wasted in each market for each product

Product related

$BOM^{rm}_{m,n}$: Production bill of materials expressing the amount of each raw material needed to produce each unit of the final product

$FPCost_m$: Price of each final product

$FlakesCost$: Price of by-product 1 (flakes, in the context of the case study)

$StarchCost$: Price of by-product 2 (starch, in the context of the case study)

$RMCost_m$: Cost of raw materials m

$WaterFoot_m$: Water footprint of each raw material m

Transportation

$TCost\_truck$: Transportation cost per tonne per km

$Transport\_Water$: Water consumption m^3 for transportation (per tonne per km)

Warehousing and packaging

WH_Pack: Water consumption for warehousing and packaging (per tonne of final product)

Others

$BigM$: Large Number

ir: Interest Rate

tr: Tax Rate

DP: Depreciation Rate

Decision Variables

Continuous and positive variables:

$X_{m,io,id,t}$: 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 g in entity i in time period t

$Aux1_{i,t}$: Amount of total final products produced in a factory i that has the technology to treat water in a time period t

Binary variables:

$TechWaterTreat_i$: 1 if technology to treat water is installed in factory i

$Tes_{i,t}$: 1 if entity i is being used in time period t

Constraints

Demand satisfaction

The demand in this problem is aggregated and considers the total quantity of final products that each market should receive. In the case studied, there are 6 different final products, of which five represent deep-fried potatoes ($m_{fp} = 1, 2, 3, 4, 5$), while the sixth product ($m_{fp} = 6$) is a unique item known as ”veggie fries,” made from fried vegetables. This way the total quantity of products that each market receives should correspond to the expected demand as represented by constraint 3.1.

$$\sum_{m,io:(m,io,i)2F^{INmfp}} X_{m,io,i,t} = dmd_{i,t} \quad \forall i \in i_{mk} \ \wedge \ t \in T \tag{3.1}$$

Demand Constraints

There are no specific quantities of each product for each market, however, two restrictions should be met. In this context, the amount of products for $m_{fp} = 1, 2, 3, 4, 5$ that each market receives should be higher than the amount of product for $m_{fp} = 6$. The reason behind this expectation is that veggie fries represent a newly introduced item specifically aimed at testing and promoting sustainable performance, and its market penetration may initially be lower compared to well-established deep-fried potato products. Thus, constraint 3.2 is needed.

$$\begin{aligned} \sum_{m,io:(m,io,i)2F^{INmfp}\wedge m2m_{pot}} X_{m,io,i,t} \geq \sum_{m,io:(m,io,i)2F^{INmfp}\wedge m2m_{newveg}} X_{m,io,i,t} \quad , \\ \forall i \in i_{mk} \ \wedge \ t \in T \end{aligned} \tag{3.2}$$

Moreover, each market should also receive more traditional potatoes $m_{fp} = 1, 2$ than the other types $m_{fp} = 3, 4, 5$, as represented by constraint 3.3. Traditional potatoes refer to classic French fries, which are deep-fried sticks of potatoes. These are the most popular items available in today’s fast-food restaurants.

$$\begin{aligned} \sum_{m,io:(m,io,i)2F^{INmfp}\wedge m2m_{asis}} X_{m,io,i,t} \geq \sum_{m,io:(m,io,i)2F^{INmfp}\wedge m2m_{newpot}} X_{m,io,i,t}, \\ \forall i \in i_{mk} \ \wedge \ t \in T \end{aligned} \tag{3.3}$$

Material balance at the warehouses

In the specific context of the industry analyzed in the case study selected, the warehouses are used as an extension of the processing phase that occurs in the factories. The products are kept in low temperatures for a cooling down process for a few days and then are shipped to the markets. Therefore, it is necessary to impose a constraint to ensure that products arriving at the warehouse are promptly dispatched to their final destinations since this is not a storage point. The goal is to maintain a continuous flow of products through the warehouse after being processed in order to conclude the process. The constraint 3.4 enforces that the products entering the warehouse must be subsequently distributed to the markets.

$$\sum_{io:(m,io,i)2F^{OUTffp}} X_{m,io,i,t} = \sum_{id:(m,id)2F^{OUTwfp}} X_{m,i,id,t}, \quad \forall i \in i_{wh} \;\wedge\; m \in m_{fp} \;\wedge\; t \in T \tag{3.4}$$

Material balance at the factories

Constraint 3.5 assures that the production in each factory must be equal to the amount of material that leaves each facility. This way, there is no stock in each factory and the final products go to the corresponding warehouse after being processed. It is considered that all the production goes directly to warehouses. The production is driven by the estimated demand per year.

$$\begin{gathered}\sum_{g:(m,g)2H1{}^{\wedge}(g,i)2H2} P_{m,g,i,t} = \sum_{id:(m,i,id)2F^{OUTffp}} X_{m,i,id,t}, \\ \forall m \in m_{fp} \;\wedge\; i \in i_f \;\wedge\; (m,i) \in V^{fac\_fp} \;\wedge\; t \in T\end{gathered} \tag{3.5}$$

Flow of raw materials from suppliers to factories

Constraint 3.6 assures that the flow of raw materials that come from suppliers must be equal to the amount needed for production, considering what is used for the production of final products and the amount that is wasted in factories.

$$\begin{gathered}\sum_{io:(m,io,i)2F^{OUTsup}} X_{m,io,i,t} = \sum_{n,g:(n,g)2H1{}^{\wedge}(g,io)2H2} P_{n,g,i,t} \times BOM^{rm}_{m,n}, \\ \forall m \in m_{rm} \;\wedge\; i \in i_f \;\wedge\; t \in T\end{gathered} \tag{3.6}$$

Maximum supplier capacity

Each supplier has a limited capacity. Thus, these capacities limited the quantities supplied for each raw material, as constrained by equation 3.7.

$$\sum_{id:(m,io,id)2F^{OUTsup}} X_{m,io,id,t} \leq sup\_cap\_max_{m,io} * Tes_{io,t} \quad \forall\; m \in m_{rm} \;\wedge\; io \in i_{sup} \;\wedge\; t \in T \tag{3.7}$$

Entities supplying raw materials

Constraint 3.8 is used in order to identify which suppliers are used in the network.

$$\sum_{(m,id):(m,i,id)2F^{OUTsup}} X_{m,i,id,t} \geq Tes_{i,t} \qquad \forall i \in i_{sup} \wedge t \in T \tag{3.8}$$

Factories capacities

Each factory has a specific capacity that must not be surpassed, as represented by equation 3.9.

$$\sum_{(m,id):(m,io,id)2F^{OUTffp}} X_{m,io,id,t} \leq fac\_cap\_max_{io} * Tes_{io,t} \quad \forall io \in i_{fac} \;\wedge\; t \in T \tag{3.9}$$

Entities used for production

The constraint 3.10 is used to identify which factories are used for production.

$$\sum_{(m,id):(m,i,id)2F^{OUTffp}} X_{m,i,id,t} \geq MinFacCap * Tes(i,t) \quad \forall i \in i_{fac} \ \wedge \ t \in T \tag{3.10}$$

Objective Functions

Economic Objective function

In order to analyze the economic performance of the network suggested by the model, an objective function was defined to maximize the Net Present Value (NPV) of the network. This formula takes into account the costs and revenues and allows the decision-maker to compare the economic impact of different decisions. The NPV is given by the expression 3.11 and it was based on the work of Cardoso et al., 2013. To determine the NPV, the cash flows (CF) from various time periods are added together, considering an interest rate denoted as 'ir'. When considering the NPV it is also measured the fixed capital investment (FCI).

$$\text{max} \quad NPV = \sum_{t2T} \frac{CF_t}{(1+ir)^t} - FCI \tag{3.11}$$

The cash flows for each time period, represented by NE_t, are determined by considering the earnings generated during each specific period as presented in equation 3.12. In the case of investments in facilities, for example, the calculation of cash flows extends to the final time period, which takes into account not only the earnings but also the salvage value. The salvage value represents the residual value obtained from selling or decommissioning the facilities at the end of their useful life. Including the salvage value in the final time period acknowledges the potential economic benefit or recovery of invested capital from the facilities. However, in this specific case study, 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 time period.

$$CF_t = \begin{cases} NE_t, & \forall t = 1, ..., NT-1 \\ NE_t + sv * FCI, & t = NT \end{cases} \tag{3.12}$$

The net earnings (NE) are defined, for each time period, by the difference between the revenues (final products and by-products sold) and the total costs. The NE is defined by the expression 3.13.

$$\begin{aligned} NE_t = (1-tr)[&FPSales + FlakesSales + StarchSales - RawMaterialsCosts - \\ &TransportationCosts - LaborCosts - ProductionCosts] + tr \times DP_t, \ \forall \ t \in T \end{aligned} \tag{3.13}$$

For the case considered, the sales are given by the sum of the revenue obtained by selling the final products (*FPSales*) and the by-products sold (*FlakesSales* and *StarchSales*). In this case, it is assumed that the company can sell all the by-products produced, however this assumption should be reconsidered depending on the industry. The costs considered in this case include transportation, labour, production and raw materials.

The revenue of the final products is given by:

$$FPSales = \sum_{(m,t):m \in m_{fp}} \sum_{io,id:(m,io,id,t) \in F^{INmfp}} X_{m,io,id,t} * FPCost_m \tag{3.14}$$

The revenue of by-product 1 is given expression 3.15 and 3.16.

$$FlakesSales = \sum_{(m,t):m \in m_{rm}} Flakes_{m,t} * FlakesCost \tag{3.15}$$

$$Flakes_{m,t} = \sum_{n,g,i:(n,g) \in H1 \wedge (n,i) \in V^{fac\_fp}} P_{n,g,i,t} * BOM^{rm}_{m,n} * Used\_flakes_n \tag{3.16}$$

The revenue of by-product 2 is given by expression 3.17.

$$StarchSales = \sum_{(t,i):i \in i_f} Aux1_{i,t} * starch\_recovered * StarchCost \tag{3.17}$$

The transportation cost are represented by expression 3.18.

$$\begin{aligned} TransportationCosts = & \sum_{(m,i,id,t):(m,i,id) \in F^{INfrm}} X_{m,i,id,t} * d\_sf_{i,id} * TCost\_truck + \\ & \sum_{(m,i,id,t):(m,i,id) \in F^{INwfp}} X_{m,i,id,t} * d\_fw_{i,id} * TCost\_truck + \\ & \sum_{(m,i,id,t):(m,i,id) \in F^{INmfp}} X_{m,i,id,t} * d\_wm_{i,id} * TCost\_truck \end{aligned} \tag{3.18}$$

To calculate labour costs, the following expression is used, taking into account that each factory produces products for multiple clients. The costs are determined based on the quantity of products produced and the hourly capacity of each factory as observed in expression 3.19.

$$LaborCosts = \sum_{(m,t):m \in m_{fp}} \sum_{(i,id):(m,i,id) \in F^{OUTffp}} X_{m,i,id,t} * LaborCost_i * Workers_i / FactoriesCapHour_i \tag{3.19}$$

The production costs are related to facilities costs, such as water, energy and other costs associated with the factory, including maintenance etc. The expression 3.20 presents the estimated costs of having a factory open.

$$\begin{aligned} ProductionCosts = & \sum_{(t,i):i \in i_f} Aux1_{i,t} * starchrecovered * StarchCost * FactoryCosts + \\ & \sum_{(m,t):m \in m_{rm}} Flakes_{m,t} * FlakesCost * FactoryCosts + \\ & \sum_{(m,t):m \in m_{fp}} \sum_{io,id:(m,io,id,t) \in F^{INmfp}} X_{m,io,id,t} * FPCost_m * FactoryCosts \end{aligned} \tag{3.20}$$

The raw materials costs are represented by expression 3.21.

$$RawMaterialsCosts = \sum_{(m,i,id,t):(m,i,id) 2 F^{OUT_{sup}}} X_{m,i,id,t} * RMCosts_m \tag{3.21}$$

Finally the last equation 3.22 describes the depreciation of the investment over the time (DP_t).

$$DP_t = DepreciationRate * FCI, \;\; \forall \;\; t \in T \tag{3.22}$$

The FCI is given by expression 3.23 and it is characterized by the number of factories where it is considered the implementation of the technology (in this case, to recover by-products from wastewater) times the cost of installing it.

$$FCI = \sum_{i 2 i_f} TechWaterTreat(i) * TechCost \tag{3.23}$$

Auxiliary Equations

In order to linearize the objective function, additional equations are needed. The following equations 3.24, 3.25 and 3.26 ensure that $Aux1_{i,t}$ corresponds to the total quantity of final products produced in factories i that have a technology to treat wastewater. This decision variable is then used in the objective functions to analyze the economic performance and quantity of raw materials (RMs) not used for FPs.

$$Aux1_{i,t} \leq \sum_{(m,g):(m,g) 2 H1 \wedge (m,i) 2 V^{fac\text{-}fp}} P_{m,g,i,t} \quad , \forall i \in i_{fac} \;\; \wedge \;\; t \in T \tag{3.24}$$

$$Aux1_{i,t} \leq BigM * TechWaterTreat_i \quad , \forall i \in i_{fac} \;\; \wedge \;\; t \in T \tag{3.25}$$

$$\begin{gathered} Aux1_{i,t} \geq \sum_{(m,g):(m,g) 2 H1 \wedge (m,i) 2 V^{fac\text{-}fp}} P_{m,g,i,t} - BigM * (1 - TechWaterTreat_i) \quad , \\ \forall i \in i_{fac} \;\; \wedge \;\; t \in T \end{gathered} \tag{3.26}$$

Environmental Objective Function

To analyze the network obtained from an environmental perspective, it is intended to minimize water consumption while also considering the water stress levels of the locations involved in the supply chain. This way, 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. The objective function is defined by the expression 3.27. By considering both water consumption and water stress of each location the model is able to choose the locations that present a lower impact on water resources.

$$\text{min} \quad WaterImpact = SupplierCons + FactoryCons + PackWhCons + TransportationCons \tag{3.27}$$

The water impact observed in the suppliers level is given by expression 3.28.

$$SupplierCons = \sum_{(m,t):m \in m_{rm}} \sum_{i,id:(m,i,id) \in F^{OUTsup}} waterfootprint_{m,i} * X_{m,i,id,t} * water\_stress_i \tag{3.28}$$

The expression 3.29 considers the water-use efficiency of the factory, the quantity produced and the water stress index of each location.

$$FactoryCons = \sum_{(i,m,t):(i,m) \in V^{fac\_fp}} wateruse_{(m,i)} * \sum_{g:(m,g) \in H1} P_{m,g,i,t} * water\_stress_i \tag{3.29}$$

Moreover, it is important to consider the indirect water consumption associated with refrigerated warehouses and the water utilized for packaging purposes as represented by expression 3.30

$$PackWhCons = \sum_{(m,i,id,t):(m,i,id) \in F^{INmfp}} pack\_wh\_cons * X_{m,i,id,t} * water\_stress_i \tag{3.30}$$

Finally, it is crucial to acknowledge that total water consumption is influenced by transportation operations at various stages. In the network under analysis, transportation occurs in three stages: from suppliers to factories, from factories to warehouses, and from warehouses to markets. Therefore, water consumption and its associated environmental impact are encompassed in expression 3.31, 3.32, 3.33 and 3.34.

$$TransportationCons = SFTransp + FWTransp + WMTransp \tag{3.31}$$

$$SFTransp = \sum_{(m,i,id,t):(m,i,id) \in F^{OUTsup}} X_{m,i,id,t} \cdot dist\_sf_{i,id} \cdot TransWaterCons \cdot water\_stress_i \tag{3.32}$$

$$FWTransp = \sum_{(m,i,id,t):(m,i,id) \in F^{OUTfac}} X_{m,i,id,t} \cdot dist\_fw_{i,id} \cdot TransWaterCons \cdot water\_stress_i \tag{3.33}$$

$$WMTransp = \sum_{(m,i,id,t):(m,i,id) \in F^{OUTwh}} X_{m,i,id,t} \cdot dist\_wm_{i,id} \cdot TransWaterCons \cdot water\_stress_i \tag{3.34}$$

Efficient use of resources: minimize the portion of RMs not used for FPs

For the case studied, it is considered that the choice of each final product has an impact on the amount that is not used in the final product production, originating by-products and waste. This objective function aims to minimize the amount of raw materials that are not used for the final product.

Equation 3.35 considers the number of final products that are wasted in each market according to each market's waste patterns plus the amount lost 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. The equation also considers the percentages of raw materials that are lost near the farmers (crop development and post-harvesting).

$$\text{min} \quad Waste = WasteMarkets + BP + Flakes + FacWaste - StarchRecover + WasteCrops \tag{3.35}$$

The quantity wasted near the final consumers is given by expression 3.36.

$$WasteMarkets = \sum_{(i,m,t):(i,m) \in V^{m\text{-}fp}} \sum_{io:(m,io,i) \in F^{INmfp}} X_{m,io,i,t} * Losses\_Market_{i,m} \tag{3.36}$$

The amount used in different byproducts is given by expression 3.37.

$$BP = \sum_{m,n,g,i,t:(n,g) \in H1 \wedge m \in m_{rm} \wedge (n,i) \in V^{facfp}} P_{n,g,i,t} * BOM^{rm}_{m,n} * Used\_by_n \tag{3.37}$$

The amount used to produce flakes is given by expression 3.38.

$$Flakes = \sum_{m,n,g,i,t:(n,g) \in H1 \wedge m \in m_{rm} \wedge (n,i) \in V^{facfp}} P_{n,g,i,t} * BOM^{rm}_{m,n} * Used\_flakes_n \tag{3.38}$$

The average quantity of RM that is wasted in the current situation is expressed by expression 3.39:

$$FacWaste = \sum_{m,n,g,i,t:(n,g) \in H1 \wedge m \in m_{rm} \wedge (n,i) \in V^{facfp}} P_{n,g,i,t} * BOM^{rm}_{m,n} * Losses\_potato \tag{3.39}$$

The amount that can be recovered using appropriate technology is given by expression 3.40. To define this portion of products, equations 3.24, 3.25 and 3.26 are needed.

$$StarchRecover = \sum_{t,i:i \in i_f} Aux1_{i,t} * starch\_recovered \tag{3.40}$$

Finally, the objective function should also account for the quantities that are lost in agriculture and post-harvest. Thus, it can be expressed by expression 3.41.

$$WasteCrops = \sum_{m,i,id,t:m \in m_{rm} \wedge (m,i,id) \in F^{OUTsup}} \left[\frac{X_{m,i,id,t}}{1 - Loss\_Agri - Loss\_PostHarv} - x_{m,i,id,t} \right] \tag{3.41}$$

Chapter 4

Case Study Description

A real case study supports and validates the model presented in chapter 3. This way, assessing the model's performance under a real context and identifying where improvements are required is possible.

The first section 4.1 describes how the network operates nowadays, providing a clear understanding of its purpose. Section 4.2 provides information related to data used to feed the model. In the subsequent section 4.3, the demand scenarios defined for the stochastic approach are identified.

4.1 Problem Description

The following case study pertains to a global fast-food chain. The boundary is the European market, and all entities are located there. The focus lies in the production of deep-fried frozen potatoes, an important item on the menu that significantly contributes to customer attraction. The fast-food chain represents an important client for the deep-fried frozen potato industry, due to the high volume of items purchased annually. All information used was sourced from publicly available data, primarily collected from sustainability reports from the companies involved.

The production of potatoes for the European market is predominantly assured by two companies (companies A and B) whose businesses are entirely dedicated to the potato industry. Their products are sold to retailers, restaurants, and food service providers worldwide. For the case under analysis, the focus is the fast-food chain mentioned until the products reach the fast-food restaurants under analysis.

Nowadays, the pressure on companies is higher to become increasingly sustainable and to meet sustainability goals by 2030. For this reason, in recent years, the two companies have been directing their efforts so that their operations reduce environmental impact. In this case, the objective is that the potato supply chain becomes more resilient to water scarcity and reduces losses and food waste. Both companies are focused on achieving a ”zero waste” policy that they are working on continuously.

Two frozen potato manufacturers (companies A and B) own and conduct operations within their factories, from receiving raw materials (RMs) to shipping Final Products (FPs). For this case, 6 different FPs are considered and for that, five RMs are needed: two varieties of potatoes, parsnips, beetroot and carrots. After leaving the factories, the products are stored in nearby warehouses for one week for a process called colling-down. Each factory has its warehouse where all products pass before being delivered to restaurants and those warehouses are only used to store the products for a short duration and then are redirected to the distribution centres of each market. Also, factories are usually located in countries that are important potato producers. Figure 4.1 presents the locations of each factory. It is observed that Company A has six factories (F8-F13), while Company B utilizes seven factories (F1-F8) to produce all the products sold in Europe. Note that for the context of this problem, each factory is dedicated to a set of products and the water-use efficiency can also vary. The map also represents the possible supplier locations for the RMs considered.

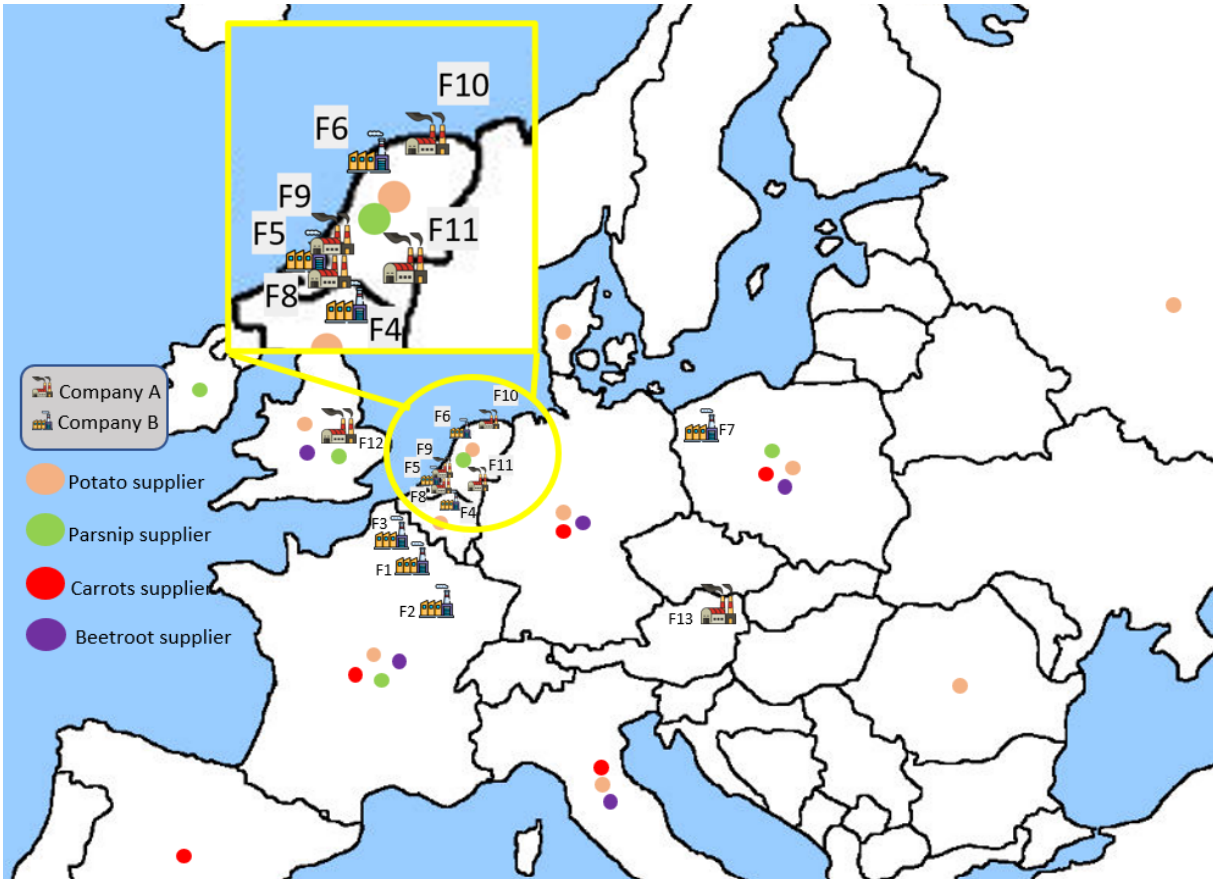

Figure 4.1: Factories where the two companies' operations currently take place and the possible suppliers' location.

Despite the six final products to be analyzed, nowadays the fast-food restaurants conduct their operations based on two final products (FP1, FP2), which will be further explored in section 4.2. By introducing different products, it is intended to test the sustainable performance of the supply chain, that is, if water consumption and waste levels are reduced, and quantify those improvements. Note that those final products are based on different raw materials that have different water requirements due to their characteristics, and the water required to produce them also varies according to each supplier. Thus, that can influence decisions regarding where to produce the FPs, where to source RMs and the quantities of each FP to produce.

Moreover, note that during the processing phase of each FP, different by-products (slivers, flakes, starch, peels) are obtained and different quantities of RMs are required. Consequently, the production volumes of each FP are intricately linked to the waste and by-products that are derived from this process.

The model also assesses the potential effects on economic performance and waste reduction by introducing a technology for recovering starch from wastewater. The processing phase takes place within a wastewater stream, and a portion of the materials is lost to this water during the process. This is why becomes important to treat the water and recover by-products, in this case, starch.

4.2 Data collection Treatment

Suppliers and crop selection

The possible suppliers for this problem are indicated in table 4.1 as well as their capacities, which were estimated based on the national production of each country. It is considered that the maximum capacity corresponds to 5% of the production in each country. This value was assumed to limit the quantity exported from each country; however, it should be reviewed for a more accurate study. Companies A and B have built long-term relationships with their suppliers, prioritizing establishing trust and mutual understanding. All data related to potato production was recovered from the Eurostat database (Eurostsat, 2022). The information about the ingredients (beetroot, carrots, and parsnips) used to produce veggie fries was collected from FAO statistics (FAO, 2021a).

Water consumption in crops varies based on various factors, such as location, and two approaches are valid to determine the water consumed. The first approach considers the average water consumption per crop worldwide, while the second one involves analyzing the water consumption per crop according to each country. The second approach was chosen for the current research since the goal is to measure the water impact per region.

Data collected on water consumption (water footprint) for various crops are presented in table 4.1. It was collected from the Agri-footprint database, using the ReCiPe2016 method, considering the process ”Ware potato, conventional, variety mix, national average, at farm gate FR”, a French national market mix. This methodology was chosen since it is one of the most common in European research (Mota et al., 2018). It includes the water requirements for potato cultivation, considering the water withdrawn for human consumption, and does not include water that potatoes receive naturally from rain. Nevertheless, the water resources are not regionalized according to the country where water is used, meaning that the water is always characterized with a factor of ”1”. In contrast, the characterization factor of specific water footprint calculation methods, such as EF3.0 and AWARE, consider water resource availability in each region. However, it is essential to note that the water footprint is used in an objective function that evaluates the water footprint multiplied by the water stress level. Using EF3.0 or Aware could lead to double counting when multiplying the water stress by a weighting factor (considered in the water footprint) in the objective function.

The different values of water footprint obtained using ReCiPe2016 vary according to regional differences in the yield and the amount of water consumed (mainly due to climatic differences and farming practices and efficiencies).

Table 4.1: Possible suppliers for the network under analysis.

Location	RM	Capacity (tons)	Water Footprint (m^3/ton)
Belgium	Potato X	198985	0.3326
Denmark	Potato X	138145	8.7693
France	Potato X	433545	10.3782
Germany	Potato X	58575	4.4433
Italy	Potato X	71735	30.5165
Netherlands	Potato X	351005	1.5767
Poland	Potato X	452795	0.7408
Romania	Potato X	134150	3.6472
Russia	Potato X	980500	1.9355
United Kingdom	Potato X	278900	7.0144
Belgium	Potato Y	198985	0.2661
Denmark	Potato Y	138145	7.0155
France	Potato Y	433545	8.3025
Germany	Potato Y	58575	3.5547
Italy	Potato Y	71735	24.4132
Netherlands	Potato Y	351005	1.2613
Poland	Potato Y	452795	0.5927
Romania	Potato Y	134150	2.9178
Russia	Potato Y	980500	1.5484
United Kingdom	Potato Y	278900	5.6115
France	Beetroot	27250	10.6154
Germany	Beetroot	41050	4.54498
Poland	Beetroot	61500	0.7578
United Kingdom	Beetroot	40050	7.1748
Italy	Beetroot	19300	31.2143
France	Carrots	84100	10.6154
Poland	Carrots	77250	0.7578
Spain	Carrots	55900	51.4149
Italy	Carrots	51900	31.2143
Germany	Carrots	46400	4.6449
United Kingdom	Parsnips	5550	7,1748
Poland	Parsnips	3550	0,7578
Netherlands	Parsnips	2050	1,6127
France	Parsnips	1650	10.6154
Ireland	Parsnips	1350	0.6887

The available information on potatoes and their water footprint does not account for the different potato varieties. In the context of the problem, it was assumed that the water footprint for variety Y is 20% lower than the values obtained using ReCiPe2016. Nevertheless, it is crucial to approach this information cautiously due to the high uncertainty level (section 5.2.2). When it comes to beetroot, carrots, and parsnips, similar challenges arise in terms of obtaining accurate data for analysis. The available information only provides data on the water footprint of carrots in the Netherlands and Belgium. An approximation method was employed to address this issue by considering the water footprint value of carrots in the Netherlands as a reference. The water footprint values were assumed to vary in a linear proportion based on the ratio of the water footprint of potatoes to carrots in the Netherlands. By considering this difference and the water footprint of potatoes in each region where carrots are produced, estimations were made for the water footprint of carrots in those regions. There is also a lack of available information regarding the water footprint of beetroot using ReCiPe2016. To address this limitation, a pragmatic approach is taken by assuming that the water footprint of beetroot in each region is equivalent to that of carrots in those respective locations. This assumption is a rough estimation, however, it is based on the understanding that beetroot is an ingredient that is used together with carrots for the production of FP6, and because of it, potential errors that would arise from considering beetroot as a separate and distinct FP have a lower impact in the results. Although employing this estimation involves a high degree of uncertainty, it provides a practical way to incorporate beetroot into the analysis within the available data and methodology constraints. For parsnips, the strategy used is the same as for beetroots since no data is available. Considering the approximations, the final result is equivalent to considering only carrots for FP6. However, the transportation of different ingredients and their costs are also considered in this context as desired.

Various indexes are available to measure the water stress level in each region, but for this research focused on Europe, data from the FAO will be utilized (FAO, 2021b). A country's water stress level is determined by comparing its annual water withdrawal to renewable freshwater resources. The values of water stress level presented in table 4.2 are provided by AQUASTAT and were obtained from the FAO database (FAO, 2021a).

Table 4.2: Water stress level (in percentage) by country.

Country	Water Stress Index (%)
Belgium	51.6
Spain	43.3
Germany	33.5
Poland	30.0
Italy	29.7
Denmark	26.4
France	23.0
Ireland	21.6
Netherlands	16.8
United Kingdom	14.4
Austria	9.6
Romania	6.0
Russia	4.1

Production

Companies A and B have different production capacities according to each factory. The capacities and type of FP produced at each location are summarized in table 4.3. Note that each factory produces FPs for different clients, so it is recommended that a specific factory not produce more than 75% of its total capacity for this particular client to ensure that it can meet the needs of other clients not included in this study. As observed in table 4.3, the estimated workforce is proportional to the capacity of each factory and it is relevant to determine the labour costs.

The different FPs are characterized in table 4.4. The raw materials listed as Potato X and Potato Y in the analysis represent different varieties of potatoes that exhibit varying patterns of water consumption during the growth process.

One of the main distinguishing factors among the products offered by the company is their cut. The

Table 4.3: Factories Characteristics.

Location	FP Produced	Capacity (ton/year)	Number of workers
F1: Harnes	FP1, FP2, FP3, FP4	197100	30
F2: Matougues	FP1, FP2, FP3, FP4	58968	26
F3: Bethune	FP1, FP2, FP5	98550	15
F4: Grobbendonk	FP5, FP6	59130	9
F5: Lewedorp	FP1, FP2, FP3, FP4	98550	15
F6: Lelystad	FP1, FP2, FP3, FP4	164250	25
F7: Chociwel	FP1, FP2, FP3, FP4	78840	12
F8: Kruiningen	FP5	63750	10
F9: Bergen	FP5	93750	15
F10: Oosterbierum	FP6	105000	16
F11: Broekhuizenvorst	FP1, FP2, FP3, FP4	138750	22
F12: Wisbech	FP1, FP2, FP3, FP4	101250	16
F13: Hollabrunn	FP1, FP2, FP3, FP4	105000	16

Table 4.4: Final products characterization.

Number	Raw Materials	Dimensions	Type of Cut
FP1	Potato X (RM1)	Normal	sticks
FP2	Potato Y (RM2)	Normal	sticks
FP3	Potato X (RM1)	Normal	slices
FP4	Potato Y (RM2)	Normal	slices
FP5	Potato X (RM1)	lower growth than expected	wedges
FP6	Carrots (RM3), Beet (RM4), Parsnips (RM5)	Normal	sticks

ingredients used for these products vary depending on the variety of potatoes used. In this case, the most widely used potato variety worldwide is Potato X. This study aims to analyze the impact of the two types (potato X and potato Y) on water consumption, as their water footprints differ. In Figure 4.2, a diagram depicts a potato cut into sticks, illustrating the portion that cannot be used in the FP since the sticks should all have approximately the same length.

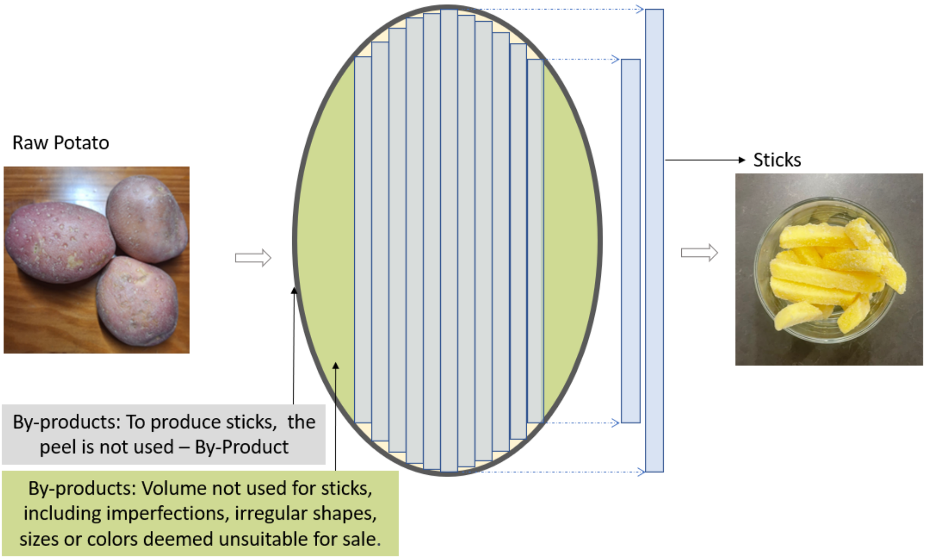

Figure 4.2: Cut 1 - Sticks.

Similarly, figures 4.3 and 4.4 diagrams were created for the potato being cut into slices and wedges, showing the respective portions that cannot be used in the FP.

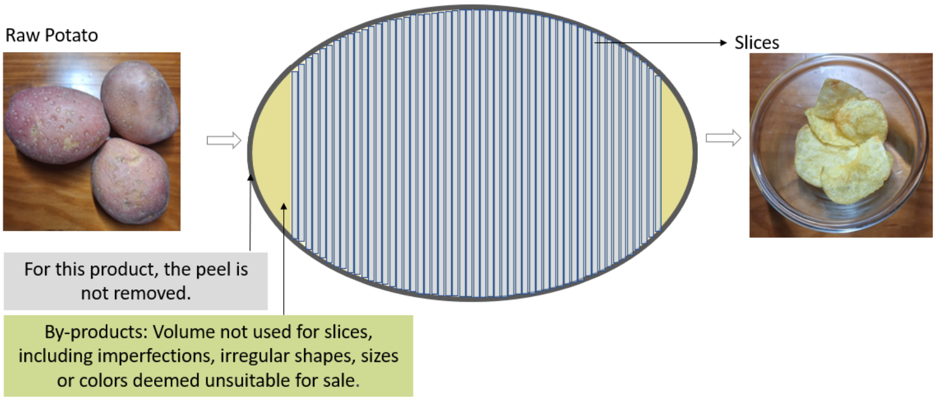

Figure 4.3: Cut 2 - Slices.

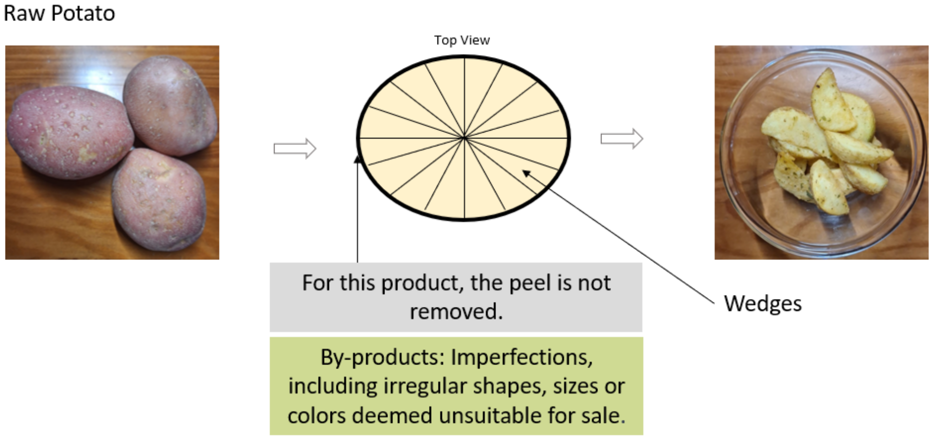

Figure 4.4: Cut 3 - Wedges.

The image in figure 4.3 highlights the portion of potato that remains unused when sliced according to specific shape requirements. It is worth noting that each potato's top and bottom parts cannot be used for slicing as they result in small pieces. This product type also includes the peel, which maximizes the usage of RMs parts. Similar conclusions are found in the FP shown in figure 4.4. The entire potato is used except for parts deemed imperfect and unsuitable for sale. These imperfections are removed, and the remaining potato is cut into wedges, ensuring minimal waste and maximum utilization of the available resources. Observe that the peel is used for the FP3, FP4, and FP5, which will lead to high water consumption for the cleaning process.

Cutting raw potatoes into slices or sticks should be of a particular and consistent size. The raw potatoes are delivered to the factories, and it is not uncommon for the trucks to be rejected if the sample does not meet the specified size range. In such cases, it would be possible to conduct a separation process to ensure that the potatoes are sorted according to their size and used for different FPs. Cutting the potatoes in wedges is typically done using smaller potatoes. Thus, this approach minimizes waste and the rejection of samples.

Table 4.5 summarizes the percentage of RMs used for each FP. Each company requires 2.5 Kg of raw potatoes to produce one kg of frozen potatoes (FP1 and FP2) in the actual context. Introducing new products to a fast food chain aims to maximize resource utilization. Note that the potato loss corresponds to 4% since both companies do not have enough resources to recover all the by-products. In addition, as potato processing takes place in water, certain parts may become immersed in the water, presenting an opportunity for reducing losses through water treatment.

Table 4.5: Usage of RMs when producing each FP.

Usage	FP 1	FP 2	FP 3	FP 4	FP 5	FP 6
Used for FP %	40	40	50	50	55	50
By-products: Flakes %	17	17	15	15	10	7
By-products: Others %	23	23	15	15	15	23
Water Evaporated %	16	16	16	16	16	16
Potato Lost %	4	4	4	4	4	4

The percentages presented in Table 4.5 were estimated using the information provided in the sustainability report of one of the two companies (LambWeston, 2022a). Figure 4.5 provides a diagram illustrating the typical utilization of potatoes in this industry. It is worth noting that, typically, when the peel is removed from the potatoes, it accounts for approximately 8% of the raw product (Vieira and Moraes, 2007). This information explains the variation in percentages for ”By-products: Others” in FP3, FP4, and FP5, as these formulations include potato peels as part of their composition.

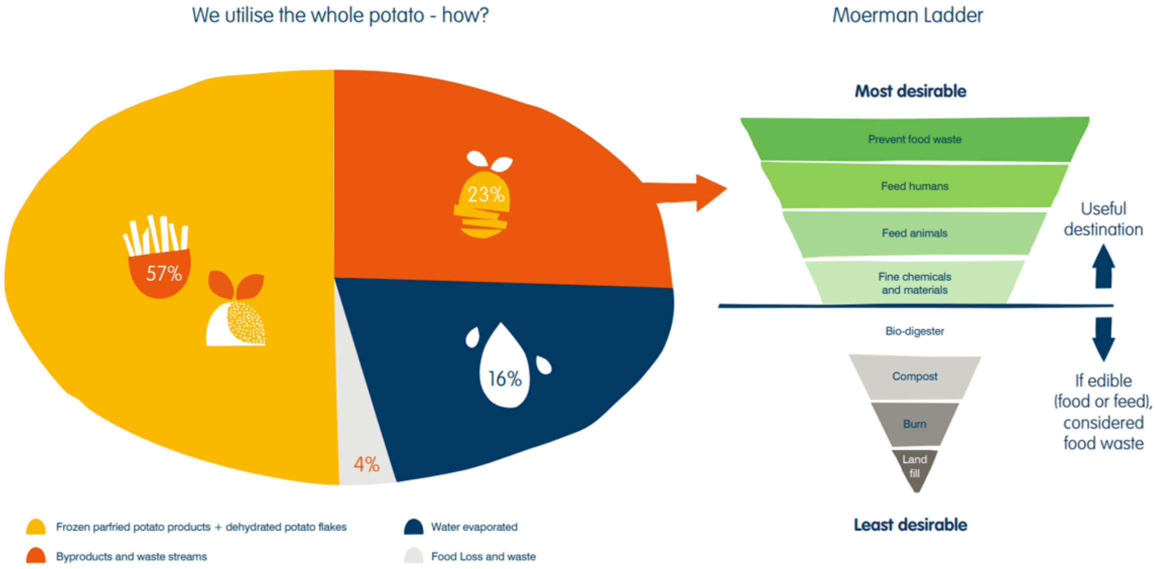

Figure 4.5: Diagram illustrating the various products obtained by one potato.
Source: From LambWeston, 2022a.

The diagram in Figure 4.5 also illustrates the Moerman Ladder, a conceptual framework employed to optimize the utilization of residual resources arising from food processing or the food supply chain. Its primary goal is to combat food waste and promote the efficient use of food resources by identifying the most effective means of adding value to waste streams. The most favourable action involves preventing food waste, achieved in this context by proposing innovative products that lead to lower waste levels. The next preferred option is to reuse the parts that cannot be used for the primary product into secondary food products, such as converting potato flakes into other derivative products. Lastly, other components, commonly classified as by-products, can be repurposed for animal feed or utilized for various chemical applications, as exemplified by starch or peels. It is worth noting that all actions highlighted in grey should be avoided whenever possible.

Various by-products can be generated during the cutting process of potatoes, including peels, starch, flakes, and slivers (Escanciano et al., 2023). The section concerning by-products pertains to a subset of RMs that can be redirected to different processes for sale to other industries for various applications. Since there are numerous possibilities and methods to reuse these products, conducting a comprehensive study on each one is impractical within the scope of this model. Consequently, the model focuses on two specific by-products for potential sale: starch and flakes. The remaining portion of the by-products is not considered waste, as there are existing methods available, according to the information provided by both companies. These methods allow for the utilization of the remaining portion of the by-products, ensuring they are not wasted.

Each factory has a water-use efficiency (WUE) associated. These values were estimated based on the information provided in the sustainability reports of some companies (McCain, 2022, McCain, 2019) aside from the values available through the ReCiPe2016 method using Agribalyze database. The values related to the water consumption for production are presented in table 4.6. In the present case, Company A utilizes water more efficiently than Company B, resulting in lower water consumption (LambWeston, 2022b). Furthermore, FPs that include peels (FP3, FP4, and FP5) imply using 10% more water during the processing than FP1 and FP2 for the cleaning process. Lastly, in FP6, the WUE is 50% higher due to the assumption that three new production lines are required, one for each ingredient. This is expected to increase water consumption as each production line operates with a closed system with a water stream.

Table 4.6: Water-use efficiency for production of each FP (m^3/ton).

WUE (m^3/ton)	FP1	FP2	FP3	FP4	FP5	FP6
F1: Harnes	7.795	7.795	8.575	8.575	-	-
F2: Matougues	7.795	7.795	8.575	8.575	-	-
F3: Bethune	7.795	7.795	-	-	8.575	-
F4: Grobbendonk	-	-	-	-	7.289	9.939
F5: Lewedrop	7.795	7.795	8.575	8.575	-	-
F6: Lelystad	7.795	7.795	8.575	8.575	-	-
F7: Chociwel	7.795	7.795	8.575	8.575	-	-
F8: Kruiningen	-	-	-	-	5.200	-
F9: Bergen	-	-	-	-	5.200	-
F10: Oosterbierum	-	-	-	-	-	7.091
F11: Broekhuizenvorst	4.727	4.727	5.200	5.200	-	-
F12: Wisbech	4.727	4.727	5.200	5.200	-	-
F13: Hollabrunn	4.727	4.727	5.200	5.200	-	-

ReCiPe2016 indicates a WUE of 7.795 m^3 of water per tonne of FP. This value was assumed to be equivalent to the WUE of company B due to its similarity with the values available in the reports. This value was obtained by considering the total amount of water used for the FP at the factory ("French fries or chips, frozen, deep-fried") and then subtracting an average value correspondent to the water used to produce the raw potato (Ware potato, conventional, variety mix, at the farm gate). This approximation can lead to minor errors, and further research could be developed to quantify the water-use efficiency per factory. Figure 4.6 represents the boundaries for each activity considered in the supply chain. The water footprint of crops involves only the activities performed by suppliers, while WUE in the factories accounts only for the water used to process potatoes inside the factory. In the production stage, one of the factors included for water consumption is the production of olive oil, which is used in manufacturing. Transportation, warehousing and packaging are not considered in the WUE for factories. The WUE value varies in proportion according to the difference in water usage in the sustainability reports of companies A and B. The factory in Belgium presents a higher WUE since the sustainability reports state that efforts were already made to increase efficiency by 15%.

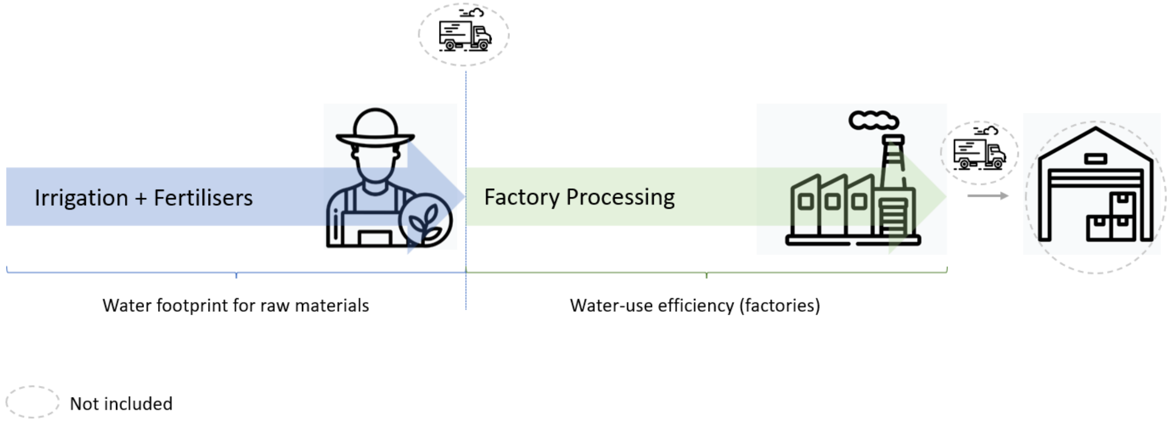

Figure 4.6: Boundaries considered to calculate water consumption for RMs and activities performed in the factories.

Markets

This study assesses the impact of introducing new FPs (FP3, FP4, FP5, FP6) in different markets. FP1 and FP2 are the ones that nowadays are sold in higher quantities. The demand of each market drives the total production of FPs; however, the idea is to follow the model's suggestions in order to analyze how many tons of each type should be produced. The markets considered for analysis are presented in Table 4.7, along with each market's projected annual demand for 2023. It is important to note that the demand represents the estimated total of potatoes consumed yearly. These estimations were derived by considering the number of restaurants per country and the volume of potatoes purchased annually in Portugal. Please be aware that these values are estimations, and for a more precise analysis, data from all restaurants across Europe would be required, which is not publicly available. Furthermore, it is expected that demand will experience a constant growth rate of 2.2% annually over the next ten years.

In Table 4.7, an estimated percentage represents the amount of food wasted in each country. These percentages indicate that, on average, a particular portion of the total quantity of potatoes purchased by customers is wasted. These estimates were derived from each country's average household waste per person (Eurostat, 2023). It is known that the average food waste across European countries for households accounts for 10%. Europe's average waste per inhabitant is approximately 70 kg per year per capita. Taking into account these values, the proportions were calculated based on the waste per inhabitant in each country (measured in kilograms), resulting in the specific percentages of waste indicated in the table. Note that these values correspond to the waste considered for FP1 and FP2. A waste of 0.5 percentage points higher than the values presented in table 4.7 was assumed for the other products deemed new to most markets (FP3, FP4, FP5 and FP6). This can be explained by the fact that the introduction of new products can cause adverse reactions in clients in the initial phase. However, note that it should be carefully analyzed in the restaurant's context and it is out of the scope of operations planning.

Table 4.7: Market demand and percentage of food waste per country.

Market	Demand in 2023 (tons)	Number of Restaurants	Food Waste per year (%) (Eurostat, 2023)
Austria	18531	195	12
Belarus	2378	25	10
Belgium	8077	85	10
Bosnia-Herzegovina	475	5	10
Bulgaria	3326	35	4
Croatia	3706	39	8
Czech Republic	10453	110	10
Denmark	760	8	11
Estonia	950	10	9
Finland	6367	67	8
France	142543	1500	9
Germany	145964	1536	11
Greece	2376	25	12
Hungary	9313	98	9
Ireland	9218	97	10
Italy	60818	640	15
Latvia	1235	13	12
Lithuania	1615	17	12
Moldavia	475	5	10
Netherlands	24612	259	8
Norway	7507	79	11
Poland	47134	496	9
Portugal	16630	175	17
Romania	7982	84	10
Serbia	2851	30	10
Slovakia	3326	35	9
Slovenia	2186	23	9
Spain	52266	550	4
Sweden	18150	191	9
Switzerland	17010	179	10
Ukraine	9788	103	10
United Kingdom	135036	1421	10

Transportation and Warehousing

Transportation between entities is assured by truck, and it is not cost-effective to have trucks transporting less than their total capacity. Each truck can transport 32 pallets, which is equivalent to 21.6

tons. Therefore, it is inefficient for a factory to produce less than the amount needed to fill a truck per month. Based on this reasoning, a minimum production capacity of 259.2 tons per year was established for each factory. It is assumed to cost 0.04 EUR per kilometer per tonne. This estimate was derived after evaluating various values utilized by Della, a transportation company (DELLA, 2022). The distances between entities were calculated considering the geographical center of each country, and using the latitude and longitude values, the Haversine formula was applied.

The current supply chain design also accounts for transportation and packaging (in the warehouses), and those quantities of water indirectly used for these activities were also considered. Since the FPs are frozen, a refrigerated system is needed in the warehouses for cooling processes, which accounts for water consumption and electricity (Staff, 2023). Different materials such as paper or plastic can be used for packaging, representing a significant water consumption. Almost all packaging involves plastic, and research in China has shown that by analyzing the LCA of plastics, nearly 1 tonne of water is needed to produce 1 tonne of plastic (Liu et al., 2023).

The estimated values for packaging and warehousing were determined using ReCiPe2016, are presented in table 4.8, and were sourced from the Agribalyse database. The value of water consumption for warehousing is primarily related to indirect water used for electricity and tap water used in daily activities in the facilities. The values related to transportation are presented in table 4.8 and were collected from the Ecoivent database for a refrigerated truck of 32 tons.

Table 4.8: Water consumption m^3 for packaging, warehousing and transportation.

Water Consumption	Packaging	Warehousing	Packaging + Warehousing	Transportation
(m^3/ton)	5.18	0.07	5.26	
$(m^3/(ton.km))$				0.0003

Other Data - Prices and Costs

Lastly, table 4.9 compiles the information regarding the costs and selling prices of FPs and by-products studied. The selling prices and cost of FPs were obtained from the Eurostat database (Eurostat, 2019). The estimated data for beetroot was sourced from ”Statistics Netherlands” (Onsharp, 2018 and Netherlands, 2019), while information on carrots was obtained from the European Commission (Commission, 2019). It is recommended to confirm the current values with the relevant companies, as prices can suddenly vary, as observed in the last year in Europe due to wars (Arndt et al., 2023) or pandemics (Consoli et al., 2023). The prices used in this research are related to the year 2019; however, it is known that the Ukraine war had a considerable impact that doubled in some sectors.

Note that the different costs of FPs are related to the fact that some (FP5 and FP6) are considered more premium and present a higher price. The price for FP3 and FP4 is slightly lower because that is regarded as a standard option and becomes less attractive. The price for FP1 was defined based on the average values found (Eurostat, 2019). It is assumed an average sales price across all markets for each final product. However, it is worth mentioning that differences in sales for the FPs can occur, with any variations primarily influenced by transportation distances.

Factories incur various costs, including labour and facilities-related expenses like water, energy, and maintenance. In this case, the labour costs vary according to the average wage in each country as presented in table 4.9. These values were obtained from the Eurostat database (Eursostat, 2022) based on data from the year 2022. It is estimated that facility costs account for approximately 30% of the revenues. However, this percentage may vary significantly across industries that strongly impact profitability.

Table 4.9: Cost of RMs, labour costs, price of FPs and by-products sold.

Raw Material	Location	Costs (EUR/ton)
Potato X/Potato Y	Belgium	97,2
	Denmark	104,7
	France	194,7
	Germany	103,3
	Italy	116,4
	Netherlands	91,4
	Poland	146,2
	Romania	164,6
	Russia	146,2
	United Kingdom	127,7
Beetroot	France	35,92
	Germany	35,92
	Poland	35,92
	United Kingdom	35,92
	Italy	35,92
Carrots	France	650
	Poland	250
	Spain	250
	Italy	420
	Germany	850
Parsnips	United Kingdom	500
	Poland	500
	Netherlands	500
	France	500
	Ireland	500
	Location	**Average Labour Cost (EUR/h)**
	France	40.8
	Belgium	43.5
	Netherlands	40.5
	Poland	12.5
	United Kingdom	30
	Austria	39
Final Product		**Price (EUR/ton)**
FP1	-	735
FP2	-	735
FP3	-	650
FP4	-	650
FP5	-	750
FP6	-	900
Flakes	-	300
Starch	-	640

To calculate the economic impact, the interest rate considered is 10% while the tax rate is 30%, based on a similar study to deal with uncertainty in SCs (Mota et al., 2018).

Other Data - Losses and Waste along the Supply Chain

To assess the extent of food waste or loss across the entire supply chain, waste and loss percentages were estimated using data from a comprehensive global study on food supply chains (Rezaei, 2017). The values considered also follow the ones presented in a study developed by FAO (Gustavsson et al., 2011), which highlights the losses and waste occurring along the entire food supply chain in different regions of the world. These percentages represent the potential waste at various stages of the supply chain as presented in figure 4.7. It is estimated that 20% of the crops are lost during the agriculture process and 6% are lost in the post-harvesting process. Moreover, it is assumed that the losses in factories correspond to 4% of the materials that arrive there. The waste near the customers is estimated to vary between 4 and 17%. Since products are frozen when they leave the factories, the risk of damage is lower, so losses are not considered to be relevant during transportation.

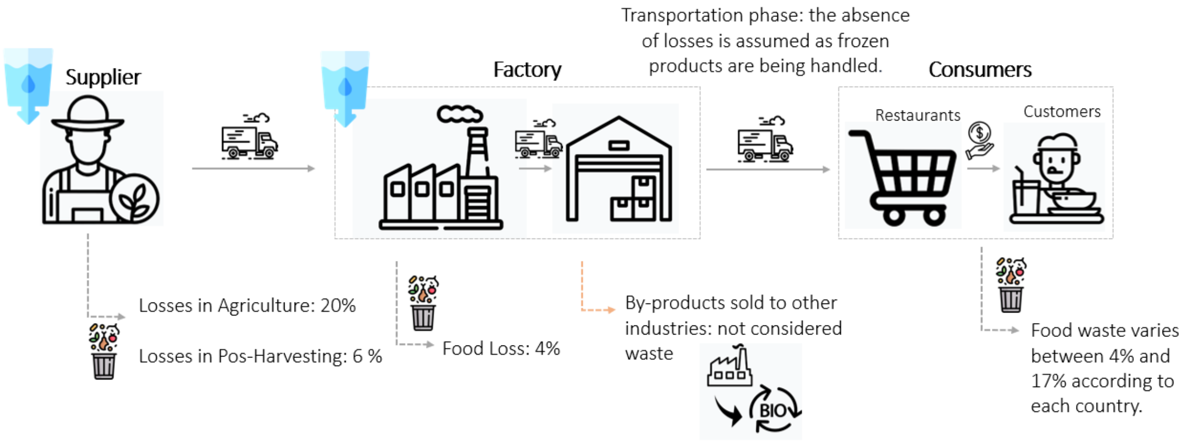

Figure 4.7: Food waste and losses along the supply chain in percentages.

A new technology can be implemented to recover about 2% of RMs and sell them as starch for other industries. The cost of implementing it is uncertain; however, it was estimated to be around 500 000 EUR. If implementing it in a real scenario, this value should be analyzed by a procurement team. Note that it is assumed that this technology has a lifespan of 10 years.

4.3 Different demand scenarios under analysis

Three scenarios are analyzed using stochastic programming, all spanning the next ten years. In stochastic programming, different scenarios represent different possible states of the system under analysis. In this context, the scenarios under investigation are related to the expected demand for the next ten years, as further explained in section 5.3.

Demand is projected to experience an annual increase of 2.2%, but given the inherent uncertainty involved, it is prudent to consider additional scenarios. These scenarios include an optimistic scenario where demand increases annually 4.4%, a pessimistic scenario where demand increases 1.1% per year, and a scenario where demand decreases 1% per year due to global instability. By doing this, companies can better understand the potential risks and opportunities and make decisions based on that.

Chapter 5

Case Study Results Analysis

This chapter examines the results of applying the model in the context of the identified case study. It is divided into three sections: Section 5.1 concentrates on the present network results, whereas Section 5.2 presents the enhancements achieved by employing the multi-objective model in the proposed solution. In this section, it is also included a sensitivity analysis for some uncertain and relevant parameters. Finally, Section 5.3 analyzes the model from the economic perspective following a stochastic approach.

To solve the problem, GAMS version 43.3.0 was used on an 11th Gen Intel(R) Core(TM) i7-1165G7 @ 2.80GHz with 16 GB of RAM, using CPLEX 22.1. The model developed is designed to be as generic as possible, but various modifications were made to accommodate different scenarios and cases.

5.1 As-Is Analysis

The first analysis is focused on each objective function individually, considering the current network structure (As-Is). After identifying the impacts of the As-Is solution, the results were compared with proposed changes (To-Be), including variations in products produced, supplier selection, factories used, and technologies installed.

The current network consists of four suppliers: France, Germany, Belgium, and the Netherlands. Additionally, the use of the following factories is considered: Harnes, Matougues, Lewedrop, Lelystad, Chociwel, Broekhuizenvorst, Wisbech and Hollabrunn. The idea is to establish a starting point by leveraging data on entities and types of FPs. This initial configuration, referred to as the AS-IS solution, serves as a baseline in terms of structure. The primary objective is to optimize this solution with a focus on maximizing profit and the results obtained (network and flows) are considered to be the As-Is solution for further comparative analysis. Additionally, it analyses the possibility of optimizing it from an environmental and resource efficiency perspective, considering water resources and waste. This approach is more conservative and does not require significant strategic changes, as the network structure remains the same. Once this optimization is achieved, we can then assess how the company can enhance its sustainable practices by exploring different long-term strategies to further improve performance (To-Be).

Figure 5.1 presents the network structure considered for the current situation. In this case, the FPs considered are only traditional french fries in sticks using both potato varieties (FP1 and FP2).

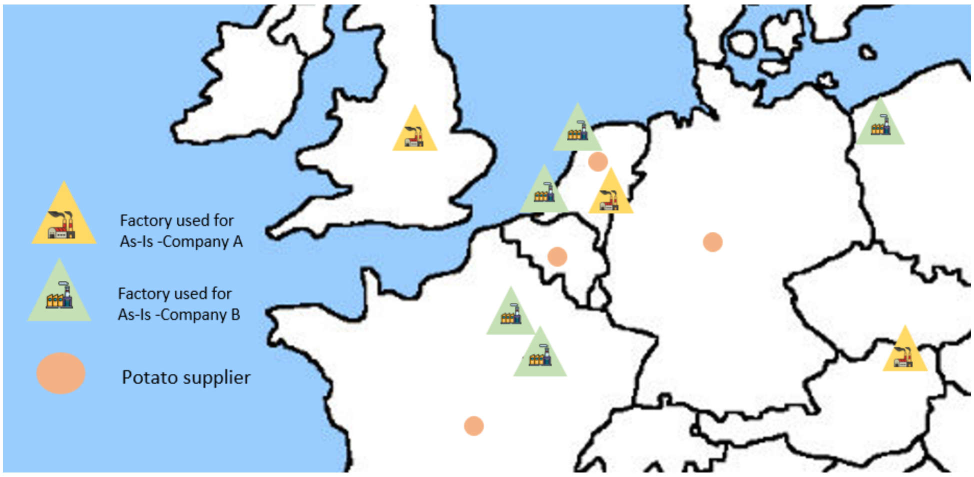

Figure 5.1: Network structure defined for the As-Is solution.

Table 5.1 presents the results obtained when optimizing the network and maximizing the NPV. The solution presented, including the structure and the flows associated, will be the focal point for the comparative study in the following analysis.

Table 5.1: As-Is Solutions, maximizing the NPV.

Objective Function	NPV (M EUR)	Water Env. Impact (M)	Waste and RM not used for FP (M tons)
A1 - Max NPV	985	3 606	17.768

To showcase the model's performance, an example of its impact on a specific market and factory during the initial period is provided. These results were verified across all flows to validate the model.

Representative flow analysis between suppliers and factories

In Figure 5.2, an illustrative representation of the inbound and outbound flows (tons of products) for period 1 at the Harnes factory is presented. In particular, the thickness of the arrows corresponds to the volume of products transported between entities, with thicker arrows denoting larger quantities.

In this case, Potato X (RM1) and Potato Y (RM2) needed in Harnes are being supplied by Belgium only. The factory receives 198.985 K tons of each raw material and produces 159.188 K tons of finished products, consisting of 79.594 K tons of FP1 and 79.594 K tons of FP2. Note that 79.594 K tons correspond to 40% of 198.985 K tons (RM received), showing that FP1 and FP2 use only 40% of the raw materials in final products as presented in table 4.5, while the other 60% are slivers, peels, flakes, starch or waste. The finished products produced in Harnes are shipped to Portugal, Spain, and France in varying quantities, as indicated by the arrows in the figure. Specifically, Spain receives 52.266 K tons of FP1, while France only receives 27.328 K tons of FP1. For FP2, 62.974 K tons are delivered to France, while Portugal receives 16.630 K tons. Those values does not represent a difference for the consumers, as both FP1 and FP2 are identical products but made using different varieties of potato.

Representative flow analysis between suppliers, factories and markets

By analyzing the model from the perspective of the markets, it is possible to evaluate if the quanti-

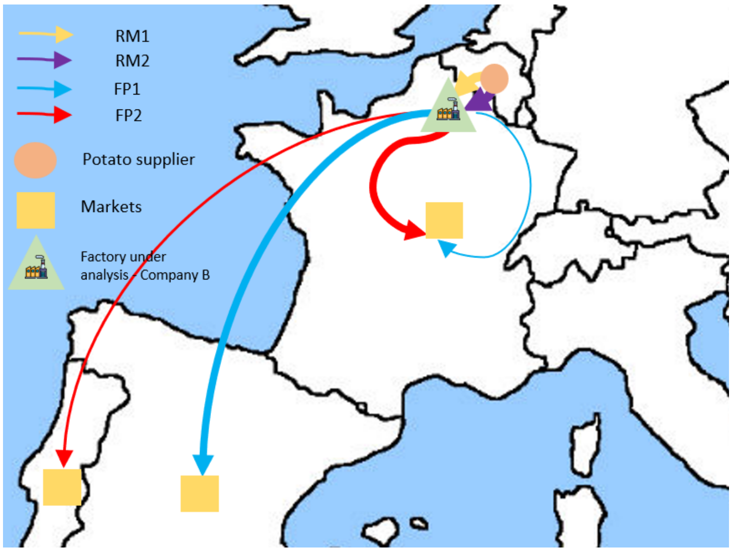

Figure 5.2: Example of flows that arrive and leave the factory in Harnes for period 1.

ties of finished products delivered to each market meet the demand and if the transportation routes are efficient. An analysis focused on the flows that arrive at the German market (the one with the highest demand) is shown in Figure 5.3. Based on these results, it can be inferred that to fulfil the demand in Germany during the first period, the supply chain must deliver 107.907 K tons of FP1 and 38.057 K tons of FP2. These finished products are manufactured in Broekhuizenvorst, with 38.057 K tons of FP2 and 62.865 K tons of FP1, as well as in Lelystad, with 45.042 K tons of FP1. The raw materials necessary to produce it are sourced from the Netherlands (for RM1) and Germany (for RM1 and RM2).

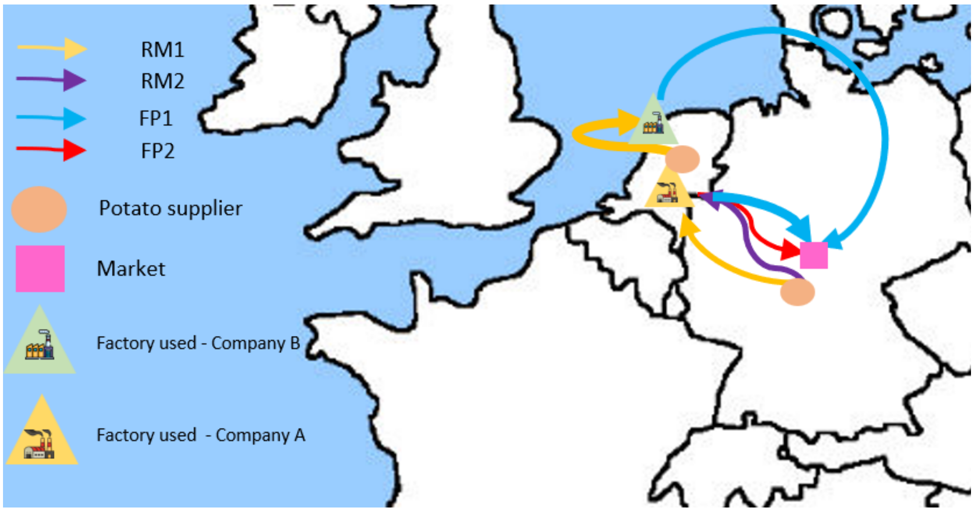

Figure 5.3: Example of flows that are needed to meet the demand in Germany in period 1.

The depicted flows represent this scenario's minimum possible distances. Indeed, in this case, since there is no information available about the specific locations of the suppliers, the model could be further improved by avoiding the assumption of using the geographical centre of each country. Instead, a more accurate analysis would consider the actual locations of the suppliers and their proximity to the manufacturing sites. This approach offers a more realistic view of supply chain dynamics, improving transportation. Figures 5.2 and 5.3 do not include the warehouses, as all products produced in each factory undergo a cooling down process in the respective warehouses near each factory.

Raw Materials Flows

An analysis of the flows from the suppliers to the factories was performed to validate the model. Table 5.2 presents each flow's quantities, aligning with each supplier's maximum capacities. When these findings are analyzed, it becomes evident that the primary factor influencing the choice of location is the pricing of raw materials, which aligns with expectations. It is worth noting that while Belgium and the Netherlands offer the most affordable options, their maximum capacity is reached. Consequently, this explains why Germany emerges as the dominant supplier, as it can fulfil demand while providing a reliable supply.

Table 5.2: Flows related to suppliers and factories being used in period 1.

Supplier	Factory	Raw Material	Flow (K tons)	Flow (%)
Belgium	Harnes	Potato variety X (RM1)	199.0	10.3
Germany	Chociwel	Potato variety X (RM1)	197.1	10.2
	Hollabrunn		36.8	1.9
Netherlands	Lewedrop	Potato variety X (RM1)	20.2	1.0
	Lelystad		279.3	14.4
	Wisbech		51.6	2.7
Total		Potato variety X (RM1)	783.9	40.6
Belgium	Harnes	Potato variety Y (RM2)	199.0	10.3
France	Matougues	Potato variety Y (RM2)	13.0	0.7
Germany	Matougues	Potato variety Y (RM2)	117.6	6.1
	Broekhuizenvorst		242.4	12.5
	Hollabrunn		225.7	11.7
Netherlands	Broekhuizenvorst	Potato variety Y (RM2)	104.4	5.4
	Lelystad		131.4	6.8
	Wisbech		115.2	6.0
Total		Potato variety Y (RM2)	1148.8	59.4

As-Is analysis for the three objectives

Table 5.3 presents the results obtained for this network design. The cells highlighted in green (diagonal) represent the best values achieved for each objective based on the current structure of the network. The values obtained to minimize waste and raw materials not used in the final products remain constant since this parameter will only change when introducing different types of final products (To-Be solution). Those results were obtained following a lexicographic approach, and the level of importance of each objective follows the order: Maximize NPV, Minimize Water Environmental Impact and Minimize Raw Materials not used for Final Products and Waste/Losses.

Table 5.3: As-Is Solutions for the current network.

Objective Function	NPV (EUR)	Water Env. Impact	Waste and RM not used for FP (tons)
A1 - Max NPV	985 308 094	3 606 129 947	17 768 375
B1 - Min Water Impact	970 743 241	3 500 467 774	17 768 375
C1 - Min Waste	985 308 094	3 606 129 947	17 768 375

Upon examining the results, it is apparent that the objective function aimed at waste reduction consistently yields the same value for the current solution. The only variation arises in the solutions that maximize NPV and minimize water impact. Nevertheless, the results remain highly similar, as all defined entities are used. It is noteworthy to observe that the water footprint of potatoes follows the order: Belgium $<$ Netherlands $<$ Germany $<$ France, and the cost of potatoes follows the order: Netherlands $<$ Belgium $<$ Germany $<$ France. These rankings contribute to the similarity in the outcomes for both objectives, in addition to the lower capacities of the Netherlands and Belgium as potato suppliers.

The products produced have an impact on the water consumed and the usage of the raw materials. Thus, it is relevant to analyse the FPs produced. The product mix for the As-Is network is presented in Figure 5.4. FP1 is produced due to the supplier's capacity, even when minimizing the environmental impact on water resources. The water footprint for the potato variety X, representing a lower water footprint, is still lower in Belgium compared to, for example, the variety Y in the Netherlands. Products are not exclusively selected using potato variety Y. Instead, it balances the capacities of suppliers with lower water footprints, even if they produce variety X. Therefore, it is concluded that selecting the right supplier becomes more critical than solely considering the water footprint of each potato variety.

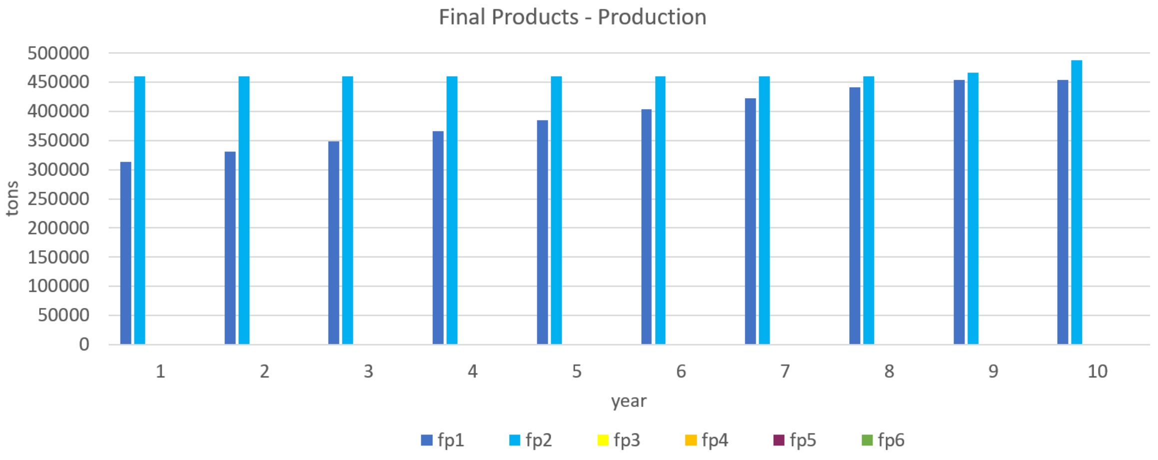

Figure 5.4: FPs production per year in the As-Is solution (A1).

Figures 5.5 and 5.6 illustrate water consumption throughout the supply chain for the two obtained solutions (A1 and B1): minimizing water impact and maximizing NPV. Note that solution A1 is the same as C1, due to the lexicographical approach followed. The quantities of water consumed in each activity are similar since the network is the same and only small changes are noticed regarding the flows.

Table 5.4 summarizes the total water consumption for each solution. As expected, the solution that minimizes water impact exhibits the lowest water volume. However, considering the given network structure, it is only possible to achieve a reduction of approximately 0.05% in water consumption. The values demonstrate that the water consumption remains approximately constant for the three objectives when using the As-Is network design.

To fulfill the demand of 8 545 918 tons over ten years, it is necessary to generate 28 881 480 tons of raw materials. For this solution, it is verified that 10% of the products are wasted near the customers,

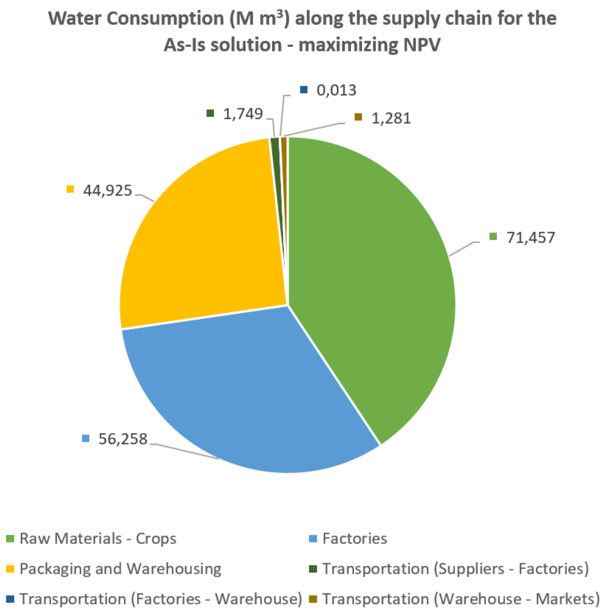

Figure 5.5: Water Consumption for the As-Is solution by maximizing the NPV.

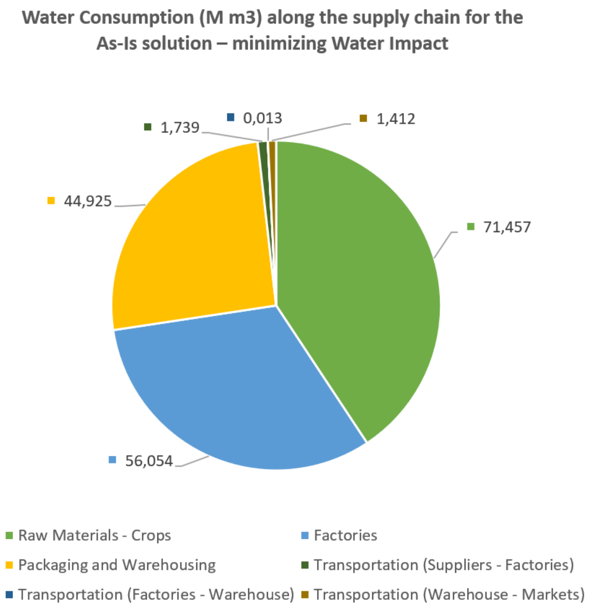

Figure 5.6: Water Consumption for the As-Is solution by minimizing the Water Impact.

Table 5.4: Total water consumption for the As-Is network considering each objective function.

Objective Function	Maximize NPV	Minimize Water Env. Impact	Minimize Waste
Total Water Consumption (Mm^3)	175.682	175.600	175.682

while in the factories, 4% of the RM are wasted and only 40% of the weight of the RMs that arrive to the factories are used for potato production. When comparing these quantities, the importance of implementing a sustainable supply chain and an effective management system to manage the available resources becomes evident. A sustainable supply chain should focus on minimizing the environmental impact of operations, reducing waste, and optimizing resource utilization throughout the product lifecycle. It is evident the importance of responsible sourcing to obtain high-quality products that lead to reduced losses, efficient production processes, and proper management of waste and by-products.

To achieve better results regarding environmental impact and optimize the use of raw materials, a new solution is developed (To-Be) using the proposed model. When implementing this solution, it is expected to achieve a more environmentally and economically sustainable system, by redesigning the network.

5.2 To-Be Analysis: Deterministic Approach

5.2.1 Single Objective Analysis considering each objective separately

This section aims to analyze the results by considering each objective function individually. Three distinct cases are identified: network design that maximizes NPV (Case A2), network design that minimizes water environmental impact (Case B2), and network design that minimizes food waste/losses and RM not used for FP (Case C2). The results of these three cases will be compared to identify factors and parameters that influence each decision. The To-Be approach takes into account different final products that can meet the demand of the markets. However, this scenario also explores the utilization of different factories and suppliers, different raw materials and technology to recover starch from wastewater. Considering that, the objective is to design a new network that enhances sustainability issues.

The introduction of new products and re-designing the network can have a positive impact on the three different cases under analysis. The purpose of these changes is not to increase the NPV, however, by implementing them, it could also be possible to increase it. Thus, the objective for the companies is to find a solution that presents advantages considering the environmental issues without worsening the economic performance. A lexicographic approach was followed, considering that in this problem it is assumed that the most relevant parameter is the NPV, followed by the water environmental impact and then the food waste/loss and RM not used for FPs. Table 5.5 presents the results obtained.

Table 5.5: Objective function results for Cases A2, B2 and C2.

Objective Function	NPV (M EUR)	Water Environmental Impact	Waste and RM not used for FP (M tons)
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

Changing strategic decisions regarding the network structure and products produced leads to improvements for the three objectives, as presented in table 5.6. The results demonstrate that it is possible to improve the NPV by 17%, when comparing cases A1 and A2. The water environmental impact can be reduced by 48% and the waste and all the RMs not used for FPs can be reduced by 20.8%.

Table 5.6: Comparison between As-Is and To-Be analyses (Cases A1 vs A2, B1 vs B2 and C1 vs C2).

Objective Function **Improvements**	NPV	Water Environmental Impact	Waste and RM not used for FP
Case A: Maximize NPV	+ 17.16 %	-	-
Case B: Minimize Water Impact	-	- 48.01 %	-
Case C: Minimize Waste/Loss	-	-	- 20.82%

When optimizing the new proposal of the network to reduce the water environmental impact, it is possible to reduce this objective by 39% (comparing A2 and B2), however, the NPV becomes negative showing that this solution is not recommended.

Regarding waste, comparing cases A2 and C2, a reduction of 4% is observed. While this value may appear negligible at first glance, when converted, it equates to a substantial 620 K tons of waste over a decade. When we consider these quantities in terms of nutritional value, assuming an average of 100 grams of potatoes providing 65 Kcal and an adult's daily consumption being around 2000 Kcal, it becomes evident that this surplus can sustain 55 000 individuals over a span of 10 years.

These results highlight the significance of conducting a multi-objective analysis to identify a solution that better aligns with the company's goals.

In order to explore the decisions leading to these outcomes and identify the most sustainable strategies, the water consumption, product mix, network design and economic analysis will be analyzed.

Water Consumption

One crucial factor to consider is the water consumption throughout the supply chain. The water environmental impact takes into account the water footprint of each activity and the water stress level index of each region. The objective is to minimize water usage in areas experiencing water scarcity, aiming for optimal resource utilization and creating a better equilibrium for the inhabitants of those regions. However, it is also essential to compare water consumption to ensure that these new solutions do not consume more water than the As-Is solution. Figure 5.7 depicts the varying water consumption for Case A2, B2, C2, and A1 (As-Is). Cases A2, B2 and C2 present better results regarding water consumption when compared with the As-Is solution. Interestingly, out of the To-Be solutions, Case B2 is the one where more water is actually being consumed. This is a result of selecting suppliers with a higher water footprint situated in regions characterized by very low water stress, such as the situation in Russia. That can be seen in the topic related to the network structure.

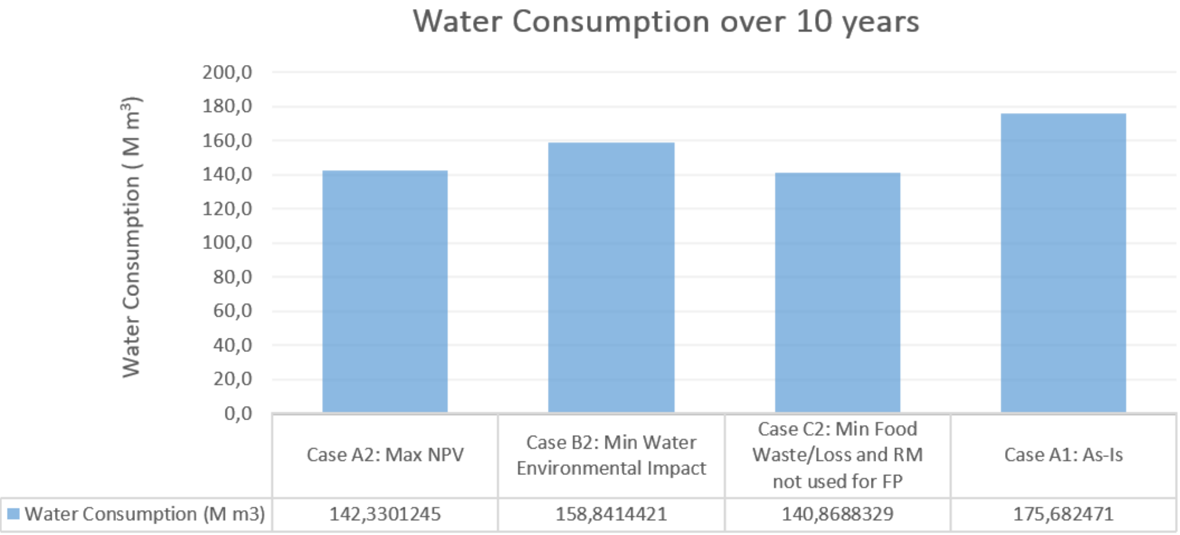

Figure 5.7: Water Consumption for cases A2, B2, C2 and A1.

Figure 5.8 represents the water consumption in each stage of the supply chain. Specifically, the water utilized for raw materials accounts for the water required in crop production, taking into account the total amount of raw materials needed, including losses that occur during agriculture and post-harvest processes. As anticipated, the production phase in factories emerges as the most water-intensive activity in the supply chain, when re-designing the network. Subsequently, the packaging and warehousing stages also exhibit significant water consumption, primarily due to the high water requirements associated with packaging. The water consumption for warehousing is much lower compared to the water used for packaging. Note that the network is not prepared to reduce water consumption in terms of packaging.

For that purpose, a new analysis would be needed in this field to evaluate techniques and methods that could lead to reduced water footprint of packaging activities. As expected, transportation is the activity that represents lower water use. This parameter is relevant when choosing the supplier's location. For example, in Case B2, the water consumed for transportation between suppliers and factories is higher due to the high distance between Russia (potato supplier) and the factories.

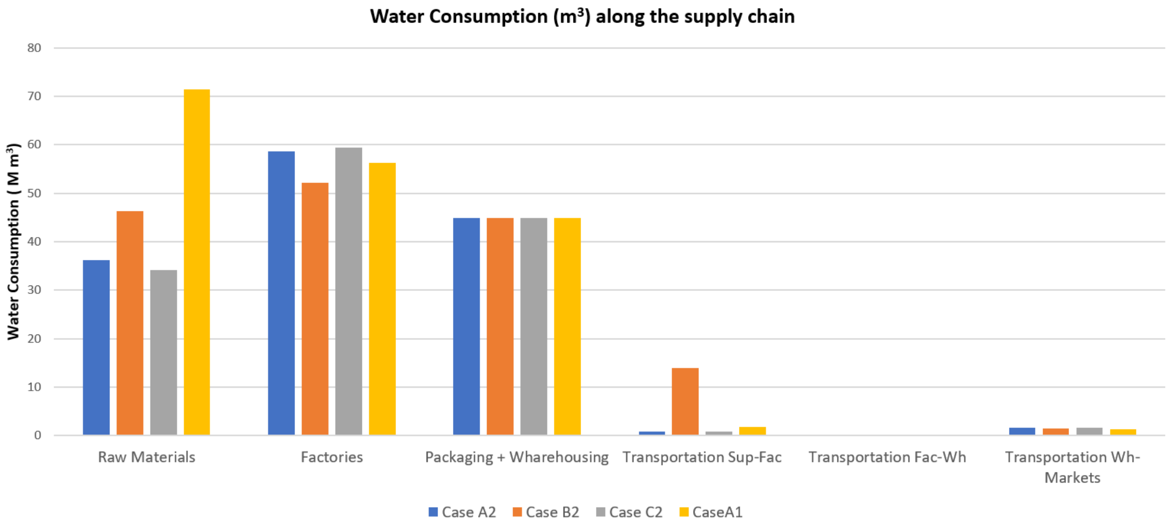

Figure 5.8: Water consumption according to each stage of the supply chain for Case A2, B2, C2 and A1.

When comparing these results with the water consumption for Case B2, significant differences are observed. The most notable disparity is found in the water consumption for raw materials, which can be attributed to the supplier's choice. It was identified that the difference is primarily related to the suppliers of potatoes. While Case B2 relies on a supplier from Russia, cases A1 and C1 source their potatoes from Belgium, the Netherlands and Germany, which have lower water footprints for potato production. Regarding the other raw materials, it was found that the second most significant difference lies in the water usage for parsnips, as France has a considerably higher water footprint for parsnip production compared to other potential suppliers. A more detailed understanding of the disparities in water consumption can be gained through an analysis of the network structure.

Network design

Table 5.7 presents a comparison of the network structures obtained for each case. It is evident from the table that the network design for cases A2 and C2 exhibits a high degree of similarity. This outcome aligns with the expectations based on the findings presented in Table 5.5, as both cases demonstrate lower variations across the three parameters in comparison to Case B2.

The results presented in Table 5.7 indicate that the supplier choices for Case B2 prioritize lower values in terms of water footprint and water stress. However, from an economic perspective, this may not be the most adequate solution due to the high costs associated with transporting products from Russia to factories located in the centre of Europe. Furthermore, relying solely on one supplier or one region for the entire operation can be risky. This emphasizes the significance of conducting a multi-

Table 5.7: Network Structure for each Case under analysis.

Cases Analyzed		Case A2	Case B2	Case C2
Factories	fMCHarnes	X	X	X
	fMCMatougues		X	
	fMCBethune	X		X
	fMCGrobbendonk	X		X
	fMCLewedrop	X	X	X
	fMCLelystad	X	X	X
	fMCChociwel	X		X
	fLWKruiningen	X	X	X
	fLWBergen	X	X	X
	fLWOosterbierum	X	X	X
	fLWBroekhuizenvorst	X	X	X
	fLWWisbech		X	
	fLWHollabrunn	X	X	X
Suppliers	Potato	Belgium Germany Netherlands	Russia	Belgium Germany Netherlands
	Beetroot	Germany	Poland	Germany
	Carrots	Poland	Poland	Poland
	Parsnips	Uk Poland Netherlands France Ireland	Uk Poland Netherlands Ireland	Uk Poland Netherlands France Ireland

objective analysis to evaluate solutions, taking into account different factors.

Final Products Produced

One important decision pertains to the production of each suggested FPs and that also influences the water consumption as observed. This decision directly impacts costs, as each final product has distinct sales prices and raw material consumption. Table 5.8 presents the final products produced for each case under analysis. The production of FP3, FP4, and FP5 should be equal or lower than the production of FP1 and FP2. Additionally, the production of FP6 should be lower than the production of FP1, FP2, FP3, FP4, and FP5. The model considers the characteristics of each product, such as water consumption and waste or losses, to adjust the production quantities.

Table 5.8: Final Products produced for each case.

Final product	FP1	FP2	FP3	FP4	FP5	FP6
Case A2: Maximize NPV	25.7%	34.9%	-	-	36.1%	3.3%
Case B2: Minimize Water Impact	30.4%	38.9%	0.8%	8.7%	18.4%	2.7%
Case C2: Minimize Food Waste/Loss	23.1%	25.3%	2.9%	8.6%	36.9%	3.3%

When analyzing Case A2, it becomes clear that due to the lower sales prices of FP3 and FP4, production is not the preferred option when considering the overall profitability of the supply chain. However, it is important to note that the costs of these products, especially when dealing with influential clients, are subject to negotiations. This implies that the food chain can influence these costs, potentially leading to different outcomes when examining the results from the perspective of Case A2. Therefore, it is observed that if the prices of these products increase, the results would change. In this particular case, it is assumed that these products are positioned as less premium compared to others in the market.

It is particularly interesting to observe that when minimizing the water environmental impact, a higher quantity of products is produced using potato variety Y (FP2 and FP4). However, the production of FP6 is comparatively lower than in cases A2 and C2 and that occurs due to limitations in parsnip supply. Once the production capacity of Ireland, Poland, Netherlands, and the United Kingdom is reached, the production of FP6 is halted. This decision is influenced by the high water footprint of parsnips in France and its water stress level, which makes it less favourable compared to other potential potato suppliers.

In Case C2, it is observed that all the products are produced, and the most preferred one is FP5. This preference arises from the better utilization of raw potatoes for FP5 in this particular case.

Economic Analysis

Furthermore, analyzing the costs and revenues associated with each network design provides valuable information about the financial viability of the systems. That helps to identify the most economically efficient solution, ensuring profitability while minimizing financial risks. In table 5.9 the costs and revenues are presented according to each case studied. Observing the information related to the revenues, it is clear that for all cases the revenues are similar, and the case where the revenue is higher is the one that considers the production in higher quantities of FP1, FP2, FP5 and FP6, the more profitable ones.

Upon comparing all the cases, it becomes apparent that the revenues remain relatively constant. The difference between the higher revenue and the lower is around 2%. This observation is expected, given that the products analyzed are similar. Consequently, the differences in terms of costs for the fast-food chain are not expected to be significantly different when choosing one final product over another.

Indeed, the analysis suggests that costs play a significant role in determining the NPV and overall profitability of each case. Case A2 and C2 exhibit similar strategic decisions, leading to comparable costs. However, Case B2 stands out due to slightly higher labour costs and a significant difference in transportation expenses. In Case B2, the absence of the factory in Chociwel, which offers lower costs, results in higher labour expenses. Additionally, the reliance on raw potatoes from Russia, which is geographically distant from the factories, leads to transportation costs ten times higher compared to cases A2 and C2. Despite considering a location in Russia closest to Europe, the vast size of the country results in substantial distances and increased costs. Furthermore, the choice of Russia leads to higher raw material costs, contributing to the higher cost of Case B2. Considering the significant impact of this specific choice on costs, it becomes evident that a feasible solution for the company would involve a combination of elements from Case A2, B2 and C2. By carefully selecting aspects from each case, such as optimizing labour costs, diversifying raw material sources, and leveraging the more cost-effective factory location, the company can achieve a more balanced and cost-efficient solution.

All the presented solutions assume the implementation of technologies that recover starch from water in all the factories being used. Despite the high initial investment required for this technology, the sales of starch compensate for the invested funds. In the model, it is assumed that all the recovered starch is sold, as it is a highly sought-after ingredient in the food industry. If this model were to be implemented in a real case, it would be necessary to identify the most important customers and estimate the demand

Table 5.9: Cost Analysis for each scenario during 10 years.

Cases Analyzed	Description	Case A2	Case B2	Case C2
Revenues (million EUR)				
Final Products	FP1	1617	1633	1451
	FP2	2190	2727	1586
	FP3	-	354	160
	FP4	-	172	478
	FP5	2315	1181	2364
	FP6	255	209	255
Flakes	potato variety x	449	418	446
	potato variety y	380	497	341
Starch		245	253	238
Total Revenue (million EUR)		7451	7444	7319
Costs (million EUR)				
Raw Materials	RM1 - potato variety X	514	971	507
	RM2 - potato variety Y	715	1433	655
	RM3 - potato variety X (small)	526	419	539
	RM4 - carrots	18	15	18
	RM5 - beetroot	5	4	5
	RM6 - parsnips	35	29	35
Transportation Cost (million EUR)				
	Suppliers - Factories	118	1856	112
	Factories - Warehouses	1.7	1.7	1.7
	Warehouses - Markets	212	197	214
Manufacturing costs (million EUR)		2235	2233	2196
Labour Costs (million EUR)		332	334	332
Investment in Technology (million EUR)		5.5	5	5.5
Total Costs (million EUR)		4717.2	7497.7	4620.2

for starch accordingly.

5.2.2 Sensitivity Analysis

The case under examination depends on various parameters estimated using available data from articles, reports, databases, and external insights. Nonetheless, a significant degree of uncertainty persists regarding the values of several of these parameters. Given the significance of these values in determining the outcomes of the model, it is crucial to study the impact of this uncertainty on the results. This can be achieved through sensitivity analysis, which allows to assess the impact of variations in the estimated parameters on the overall results. By developing a sensitivity analysis, it is possible to better understand the robustness and reliability of the model studied, and identify areas where additional research may be needed to improve the accuracy.

Several factors have been identified due to the significant influence on the final products produced. These factors encompass water-use efficiency within factories, the water footprint associated with raw materials, the supplier's capacity for veggie fries and the food waste associated with the final consumers.

Water footprint for potato variety Y

Due to the lack of available information on water footprints for different varieties of potatoes, the parameter representing the water footprint of potato variety Y is based on a rough assumption. As a result, a sensitivity analysis was conducted to determine if strategic decisions were affected by variations in this parameter. It is crucial to assess whether changes were observed in the selection of factories, suppliers, and final products produced as a consequence.

Table 5.10 illustrates the various cases analyzed, showing the water footprint percentages compared to potato variety X. In this context, the percentages represent the proportion of water consumed by variety Y relative to potato variety X. For instance, if variety Y has a water footprint represented by the percentage 90%, it indicates that it consumes 10% less water compared to variety X. The values presented were obtained by minimizing the water environmental impact, and then, it was verified how the NPV and the usage of resources were affected for the solution that minimizes the water environmental impact.

Table 5.10: Results related to the water environmental impact according to different values of the water footprint for potato variety Y.

Water footprint of variety Y	95%	90%	85%	80% (base value)	75%	70%	65%
Minimize Water Impact (x 10^6)	1831	1827	1824	1820	1816	1812	1808
Maximize NPV (M EUR)	-23.19	-23.19	-23.19	-23.19	-23.19	-23.19	-23.19
Minimize Waste (M tons)	15.45	15.45	15.45	15.45	15.45	15.45	15.45

For all the solutions obtained, when varying the values of water footprint, the water impact decreases by decreasing the values of the water footprint, however, the network design of the supply chain remains constant, meaning that the suppliers are the same as well as the factories selected for production. It is particularly interesting to observe that the value related to waste and raw materials not used for final products remains constant, which indicates that the quantities of products produced according to each type of cut over the years are the same. However, the difference in terms of product mix is related to the quantities of products containing variety X and Y. Table 5.11 presents the amounts of products produced using variety X and Y according to the different values of water footprint analyzed.

Table 5.11: Product mix associated to each different of water footprints of potato variety Y.

Water footprint of potato variety Y	95%	80% (base value)	65%
Quantity of FP containing potato variety X (tons)	4 394 272	4 318 049	4 282 413
Quantity of FP containing potato variety Y (tons)	3 922 000	3 998 223	4 033 860
Total	8 316 272	8 316 272	8 316 272

Again, the percentages in table 5.11 are related to the percentage of water footprint compared to variety X. The quantity of variety Y increases when the water footprint is lower, as expected. It is assumed that the final product using variety X or Y should have the same taste, texture and colour however, if this assumption is not verified, it can impact sales according to consumers' preferences.

Water-use efficiency in factories for veggie fries production

The water consumption in the factories was estimated based on data provided by two companies specializing in potato production with dedicated production lines for specific products. However, when considering the introduction of veggie fries into the production lines, additional vegetables such as parsnips, beetroot, and carrots would need to be processed. This would lead to an increase in the number of production lines and potentially result in a lower water-use efficiency compared to the production of regular potatoes. It is important to note that the exact water consumption values for veggie fries are currently unknown since they are not being produced by either of the companies.

To assess the impact of the water consumption factor on the environment, a sensitivity analysis focused on the water's environmental impact was carried out. The analysis involved testing a water-use efficiency similar to that used for potatoes with peels. Specifically, first, it was assumed a 10% increase in water consumption compared to the production of potato sticks. However, when considering a 50% increase (base value) the maximum capacity is already reached and because of it, no differences are found. FP6 is made of three different ingredients, which means that in the worst-case scenario, three different production lines would be needed, which corresponds to an increase of 200% in water consumption compared to the production of potato sticks. Thus, table 5.12 presents the differences in the objective functions for different water-use efficiencies for this specific product.

Table 5.12: Results related to the water environmental impact according to different values of water-use efficiency for FP6.

Water-use efficiency for FP6 considering the production of sticks	150% (base value)	200%	250%	300%
Minimize Water Impact (x 10^6)	1820	1827	1830	1830
Maximize NPV (M EUR)	-23.19	-38.14	-58.25	-58.25
Minimize Waste (M tons)	15.45	15.53	15.63	15.63
Production of FP6	X (full capacity)	X (no full capacity)	-	-

The production of veggie fries (FP6) has been empirically proven to result in a reduction in the environmental impact on water resources. When comparing the scenario where FP6 is not produced to a situation where production is optimized according to available capacities, a substantial reduction of approximately 0.5% in water environmental impacts is observed. Note that when increasing the water consumption to produce FP6, the results show that the quantities of FP6 start lowering according to the supplier's water footprint. For an increase of 100% in the water consumption in factories, the model only produces FP6 using the suppliers that present lower water consumption.

Supplier's capacity of tubers for veggie fries

The production of veggie fries is primarily constrained by the capacity of parsnips. This finding indicates that the availability of parsnips significantly affects the overall output of veggie fries.

Parsnips, one of the three ingredients in veggie fries, are produced in low quantities in Europe, and their capacity values are significantly lower compared to the capacities of the other two ingredients.

The purpose of this analysis is to evaluate the impact of varying parsnips' capacity on the overall performance and outcomes of the production. By adjusting the capacity of parsnips and observing the resulting changes in the objective functions, it is possible to understand the relationship between capacity and the overall effectiveness of the veggie fries production in the three objectives.

It is intended to identify the optimal capacity of parsnips that maximizes the desired outcomes across all three objective functions. This analysis could help decision-makers determine whether it would be beneficial to consider outsourcing parsnips from other regions, rather than solely relying on products produced within Europe. Table 5.13 presents the results according to the variation of parsnip capacity for each objective function.

Table 5.13: Results obtained for each objective function through variation of parsnips capacity.

Parsnips Capacity	400%	300%	200%	100%
Maximize NPV (M EUR)	1162.665	1160.907	1157.995	1154.419
Minimize Water Impact	2.959 x 10^9	2.951 x 10^9	2.966 x 10^9	2.989 x 10^9
Minimize Waste (M tons)	14.17	14.31	14.50	14.69

The parsnip capacity was increased by different percentages, ranging from 200% to 400%. As the parsnip capacity increased, the results showed a trend in the objective function values. For the objective of maximizing NPV, the values increased gradually with each increase in parsnip capacity, which means that higher veggie fries production leads to improved financial performance, as expected.

On the other side, for the objective that minimizes water environmental impact, based on the solutions that maximize economic performance it is observed that the values decrease, which proves that the production of veggie fries leads to an improvement regarding water concerns. When the parsnip capacity is 4 times higher, the value of water environmental impact increases compared to the solution with parsnip capacity 3 times higher, which means that the production of veggie fries leads to higher water consumption in regions where water is more scarce.

Regarding the objective of minimizing waste and Raw Materials not used for Final Products, the results showed a gradual decrease in waste quantities as parsnip capacity increased. This suggests that a higher parsnip capacity may result in decreased waste generation during the production process.

Food Waste in the Markets

It has been determined that the waste percentage in the new final products introduced in the market is 0.5 percentage points higher. This disparity is attributed to the potential lower acceptance levels that these new products might experience. However, the increase remains relatively low since, in a fast food chain like the one under analysis, products are thoroughly tested beforehand, and such a scenario is not expected.

Nonetheless, considering the primary focus on waste reduction and the ongoing efforts to adapt production accordingly, the model was tested with a hypothetical scenario where waste for the new FP in the market is assumed to be twice as high. In this particular scenario, it has been observed that the production of new products does not deviate from the initial scenario (0.5 percentage points difference between both types of FP), as the production per type of product remains the same. This result indicates that it is more effective to reduce waste in the production phase.

5.2.3 Impact of the choice of water stress level index

There are two widely accepted methods for measuring the level of water stress in each country or region: Aquastat (by FAO) and Aqueduct. For this research, the Aquastat method will be used, but it is relevant also to test the model results using the values provided by Aqueduct.

The main difference between these two methods lies in the scale of measurement. Aquastat uses a scale ranging from 0 to 100, expressed as a percentage, while Aqueduct employs a scale ranging from 0 to 5. Since the objective function pertaining to water resources' environmental impact is constructed by multiplying water consumption by the level of water stress in each region, the disparity in scales can have a significant impact on the network design.

Regarding the measurement of water stress, both methods take into account various factors such as water availability, population, and water use. Aquastat focuses on national-level assessments, while Aqueduct provides a more detailed evaluation at a sub-national level. These methods aim to provide insights into the level of water stress experienced in different areas, aiding in the assessment of water resource management and potential risks. Table 5.14 provides an overview related to the values obtained from Aqueduct methodology.

Table 5.14: Water stress level, according to Aqueduct, by country.

Country	Water Stress Index (0-5)
Belgium	3.89
Spain	3.74
Germany	2.14
Poland	1.48
Italy	3.01
Denmark	2.08
France	2.19
Ireland	0.46
Netherlands	1.61
United Kingdom	1.40
Austria	0.27
Romania	1.85
Russia	1

Appendix A provides a graphical representation of both scales to verify that the differences are not only based on the scale used and that one scale can consider higher levels of water stress in a specific area compared to the other.

This parameter is critical for the objective function related to the minimization of the water impact, which involves the level of water stress of each location.

By analyzing the model using the water stress level provided by Aquastat and Aqueduct, two specific networks are obtained. The results collected are summarized in table 5.15. These results were obtained through a lexicographical analysis, which involved prioritizing three criteria: Water Environmental Impact, NPV, and Waste. The NPV values were determined while maintaining the lowest water environmental impact and waste calculations were performed by simultaneously minimizing the water environmental impact and maximizing NPV.

Table 5.15: Network Results based on Aquastat vs Aqueduct Water Stress Levels.

Water Stress Level Index	Water Impact (Millions)	NPV (Millions EUR)	Waste (Millions tons)
Aquastat	1819.62	-23.19	15.45
Aqueduct	166.94	775.98	14.41
Aquastat Normalized	79.09	-23.17	15.45
Aqueduct Normalized	78.09	774.93	14.41

Note that this study considered two approaches: using the normal index and using the same scale but normalizing the values based on the value of water stress level in France. Indeed, when employing a normalized scale to assess water impact, it becomes evident that variations in the magnitude of the environmental impact are noticeable. However, for NPV and Waste, the values were similar when using these two approaches, with the differences attributed to minor changes in the product mix.

Upon observing the values in table 5.15, it is evident that there are significant disparities in the results. Specifically, the objective function designed to minimize water environmental impact yields a value without any specified units of measure, since this value is derived by multiplying the water usage (measured in cubic meters, m^3) by the water stress level index specific to each region. However, due to the utilization of two distinct scales for the water stress level measurement (ranging from 0 to 100 and from 0 to 5), the resulting objective function values have different magnitudes. Moreover, it is also noticeable the disparity obtained for the NPV value when using both scales. The analysis using Aquastat provided a negative NPV, while the other one provided a positive value. In terms of waste, both combinations provide similar values.

The disparity of values observed is due to the different strategic decisions taken for both situations. Table 5.16 provides an overview of the decisions made for both analyzes. It is worth mentioning that regardless of whether the scale was normalized or not, the strategic decisions remained the same. The normalization of values did not alter the overall conclusions or recommendations regarding the strategic choices made in the study. In conclusion, the observed differences can be attributed to variations in the definition of each scale and the disparities in results are directly linked to how each scale is defined.

The suppliers differ due to the use of different scales for measuring water stress. Belgium, Netherlands, and Poland have lower water footprints for potatoes, indicating optimized irrigation systems and water consumption processes in these regions. On the other side, Russia has a lower water stress index. Aquastat data states Belgium with a 52% water stress level, while Russia has 4%. Therefore, different data ranges lead to different results. The use of Aquastat data leads to the selection of locations with lower water stress levels, while the choice of Aqueduct data provides results focused on locations with lower water footprints. Both approaches are valid, and decision-makers should choose the one that better aligns with the network characteristics desired. The same reasoning is applied for factories choice, however, for these entities, the choice is more restricted due to capacity limitations and the existence of specialized factories for specific final products.

Table 5.16: Network Results based on Aquastat vs Aqueduct Water Stress Levels.

Water Stress Level Index		Aquastat	Aqueduct
Product Mix		FP1 FP2 FP3 FP4 FP5 FP6	FP1 FP2 FP3 FP4 FP5 FP6
Factories	fMCHarnes	X	
	fMCMatougues	X	
	fMCBethune		X
	fMCGrobbendonk		
	fMCLewedrop	X	X
	fMCLelystad	X	X
	fMCChociwel		X
	fLWKruiningen	X	X
	fLWBergen	X	X
	fLWOosterbierum		
	fLWBroekhuizenvorst	X	X
	fLWWisbech	X	X
	fLWHollabrunn	X	X
Suppliers - potato		Russia	Belgium, Netherlands, Poland
Suppliers - beetroot		Poland	Poland
Suppliers - carrots		Poland	Poland
Suppliers - parsnips		Poland, Uk Netherlands, Ireland	Poland, Uk Netherlands, Ireland

Although the products produced are the same, the individual quantities of each final product vary significantly depending on the use of different databases for the water stress level index. This way, for a better understanding, figure 5.9 provides an overview of the quantities produced of each final product. Using Aquastat measures results in a higher proportion of traditional French fries (approximately 70%) compared to the model using Aqueduct Data (around 50%). Note that this choice can influence customer satisfaction and should be taken into account by the decision-makers.

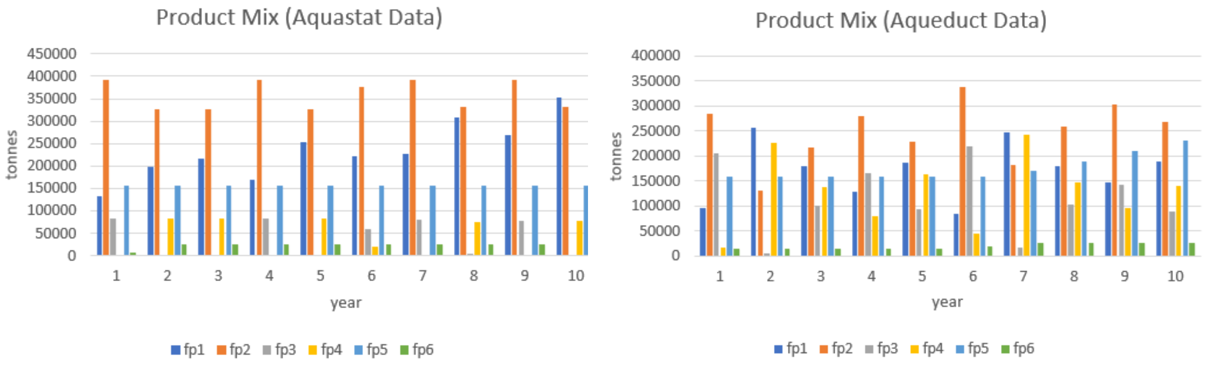

Figure 5.9: Quantities of FP per year, according to the usage of two water stress level indexes.

Furthermore, it should be noted that the selection of the water stress index can significantly impact water consumption levels. Therefore, the graphs in Figure 5.10 represent the water consumption for both analyzes, taking into account both indexes.

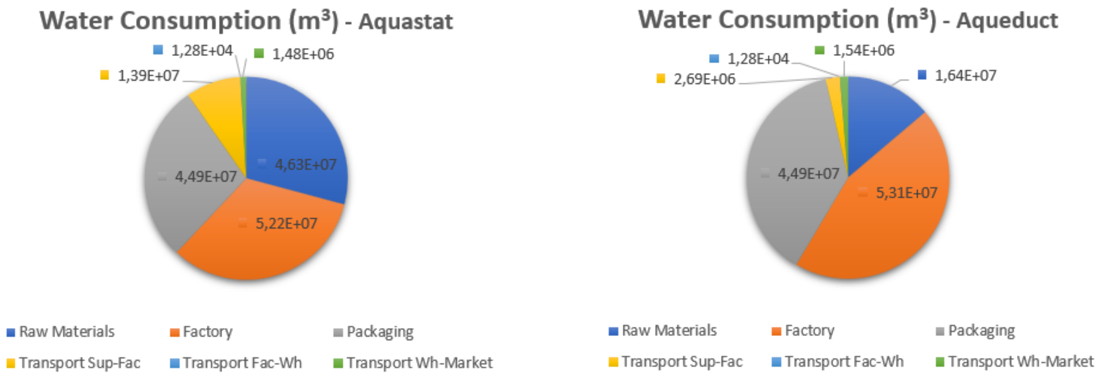

Figure 5.10: Water consumption in m^3 per activity, according to the usage of the two water stress level indexes: Aquastat and Aqueduct.

As observed in Figure 5.10, by using different methods, the total water consumption varies. Using data from Aquastat, the total water consumption amounts to 159 million of m^3, whereas when using Aqueduct the water consumption stands at 119 million of m^3. Nevertheless, there are some activities in which water consumption remains constant. This is the case, for water indirectly consumed for transportation between factories and warehouses, as well as for packaging, since these are constant values. The most impactful change is related to agriculture. The model considering data from Aquastat considers as suppliers only Russia which has a higher water footprint for potatoes compared to Belgium, Poland and the Netherlands. The consumption for factories and the transportation between factories and final markets are similar. By having only Russia as a supplier for potatoes, the distance from factories is much higher which has a direct impact on the water consumed indirectly for transportation.

These findings demonstrate the influence of using different measurement scales or indexes. It is essential to consider the network structure and strike a balance between expectations regarding water-use efficiency and water footprint versus water stress in different regions. This comprehensive analysis will enable informed decision-making to achieve the expected results.

5.2.4 Multi-objective analysis using lexicographic optimization and the epsilon constraint method

The next step involves delving into the integration of these objectives and uncovering potential solutions that can effectively explore the compromise solution space between the objectives defined.

The set of solutions obtained through the multi-objective method and the lexicographical approach is commonly referred to as the Pareto front or Pareto set. The Pareto front represents the trade-offs between different objectives in a multi-objective optimization problem. A solution is considered to be in the Pareto front if there is no other solution that can improve the result of one objective function without simultaneously worsening the result of another objective function (Goos et al., 2007).

The Multi-objective mathematical programming methods can be categorized according to three types based on the stage at which the decision-maker provides their input: priori, interactive, and posterior (Mavrotas, 2009). The priori methods are the most popular according to Mavrotas (Mavrotas, 2009), however, the interactive and posteriori methods offer more comprehensive information to the decision-maker. The posteriori approach is the one that provides more detailed information by presenting the entire Pareto set before the final decision is made, which reinforces the confidence in the decision made.

The chosen method to be applied is the posteriori, specifically an improved version of the ϵ-constraint method known as the augmented ϵ-constraint method. This improved version accelerates the process by avoiding redundant iterations. The method is widely recognized as an effective approach and is commonly used by various researchers in developing multi-objective optimization models. Consequently, all solutions generated through this approach are efficient, providing a more reliable basis for decision-making.

In the subsequent analysis, the chosen method is applied. The ϵ-constraint method utilizes a lexicographical approach to generate a payoff table. The method relies on the assumption that each objective function is optimized individually, starting with the most relevant one for the decision-maker. The optimal solution obtained for the prioritized objective function is then added as a constraint to the model, ensuring that it remains unchanged. An iterative process continues by optimizing the following objective functions and adding them as a constraint while preserving the previously obtained optimal solution and it is repeated until all objective functions are run. To do that, it was used the algorithm developed by Mavrotas.

The analysis was carried out in four steps. The initial three steps involved comparing each pair of objectives, by building three Pareto fronts, and, in the fourth step, a Pareto analysis was conducted involving all three objectives simultaneously.

NPV vs Water Environmental Impact - Trade-off

Firstly, it was evaluated how the water environmental impact changed by increasing the value of the objective related to the NPV. The results obtained are presented in figure 5.11.

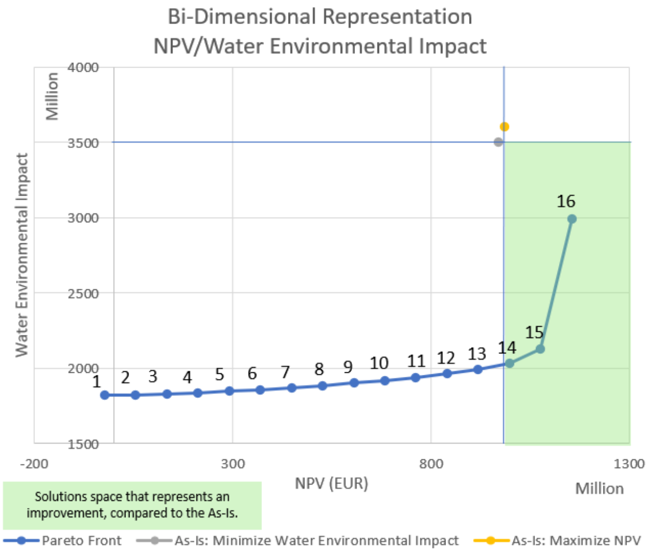

Figure 5.11: Bi-Dimensional Representation of the Pareto Front for the water environmental impact through varying the NPV, including the As-Is solution for the NPV and water environmental impact.

Upon careful observation, it is evident that the final solution 16 depicted in Figure 5.11 exhibits a significantly high water impact value. Notably, for a mere 7% increase in the NPV, the water impact surged by a staggering 41% (solution 16). Consequently, it can be concluded that decisions prioritizing optimal NPV, when assessed from a sustainability standpoint, should be reconsidered, as the increase in NPV does not justify the significant increase in water environmental impact. This difference in water impact values is primarily attributed to the selection of suppliers and the production of specific final products. For solution 16 depicted in the graph, there is a higher production quantity of FP5, which consumes more potato variety X, representing higher water consumption, and a substitution of Poland as a supplier with Germany, which has higher water stress level and higher water consumption. These factors contribute to the observed disparity in water impact values between the last solution in the graph and the other ones with an NPV slightly lower. It is anticipated that by investing in new technologies, such as starch recovery from water, and making alternative supplier choices, the NPV is likely to decrease. However, despite the expected decrease in NPV, the Pareto analysis still identifies three solutions that demonstrate higher NPV and lower water environmental impact values compared to the best results obtained from the As-Is network. These promising solutions are highlighted in green in Figure 5.11.

NPV vs Waste/Loss and RMs not used for FPs - Trade-off

An evaluation was conducted to analyze the relationship between the objective of maximizing the NPV and the levels of waste/losses and the RMs not used for FPs. The results are depicted in Figures 5.12 and 5.13, illustrating the obtained Pareto Front.

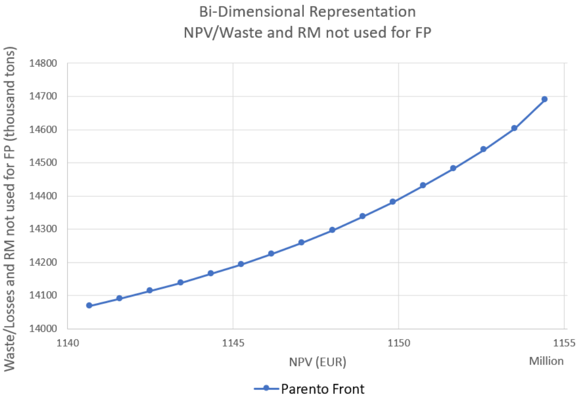

Figure 5.12: Bi-Dimensional Representation of the Pareto Front for the waste/losses and RM not used for FP through varying the NPV.

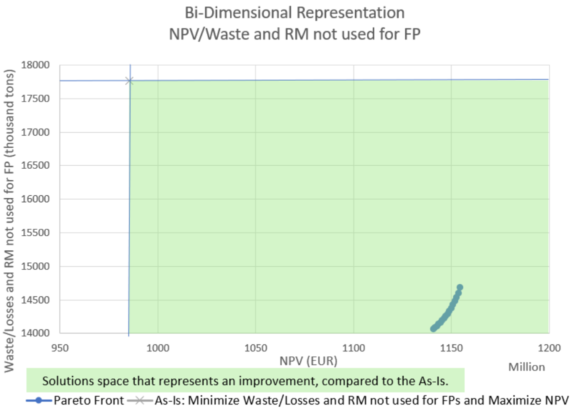

Figure 5.13: Bi-Dimensional Representation of the Pareto Front for the waste/losses and RMs not used for FPs through varying the NPV, including the As-Is solution for the NPV and Waste/Losses levels.

It is important to note that as the NPV increases, there is a corresponding increase in waste and losses. However, a notable observation arises when examining the last two solutions on the Pareto Front (Figure 5.12). For a small increase of 0.08% in NPV, the waste level increases by 0.6%. This finding suggests that when efforts are made to increase NPV, there may be an increase in waste and losses. However, as NPV continues to rise, the additional gains in NPV come at a higher cost in terms of increased waste.

Figure 5.13 shows that all the solutions obtained in the Pareto Front outperform the best values achieved in the As-Is network. Note that for the As-Is network, the solution that maximizes NPV and the one that minimizes waste is the same. By producing other FPs the waste is reduced. Therefore, any solution derived from the To-Be model would yield superior outcomes. The objective related to waste reduction becomes comparatively less critical when compared to the objectives of maximizing NPV and minimizing water environmental impact. It is crucial to note that the NPV and Water Impact objectives carry more weight as their optimization is essential in avoiding outcomes that may be worse than the current solution.

Waste/loss and RMs not used for FPs vs Water environmental impact - Trade-off

The third step is to analyze how the water environmental impact is affected by different quantities of waste/loss and RMs not used for FPs. Figures 5.14 and 5.15 illustrate the Pareto results obtained. Upon observing the results in Figure 5.15, it is concluded that all the solutions in the Pareto front outperform the results obtained with the As-Is solution. The analysis also reveals that minimizing food waste/loss increases the water environmental impact. The solution that presents the worst value in terms of waste (Case B2) is associated with a higher production of FP2, representing lower water consumption but more waste associated, and a lower production of FP5 and FP6, which lead to higher water consumption but lower waste. To lower the waste levels, the production of FP5 should increase, since this is the one that leads to lower waste, however, that product is made from potato variety X, which leads to higher water consumption.

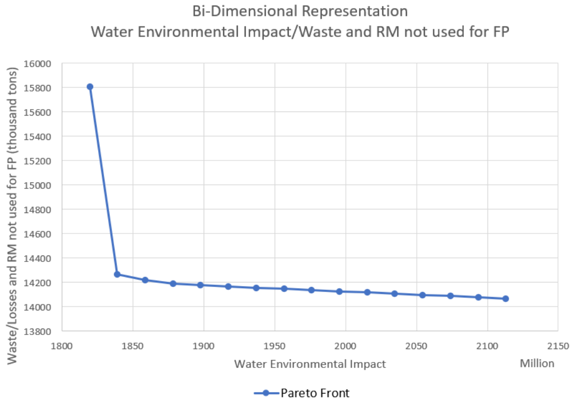

Figure 5.14: Bi-Dimensional Representation of the Pareto Front for Waste/Loss and RM not used for FP through varying the water environmental impact.

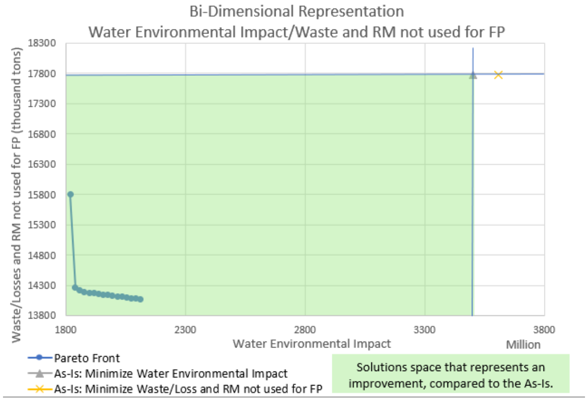

Figure 5.15: Bi-Dimensional Representation of the Pareto Front for Waste/Loss and RM not used for FP through varying the water environmental impact, including the As-Is solution for both objectives.

5.2.5 Proposed To-Be solution

To further evaluate the solutions presented in Figure 5.11, considering the trade-off between NPV and water environmental impact, the model was re-run to identify, for each solution, the minimum level of waste and RM not used for FP, using a lexicographical approach.

The Pareto front obtained is presented in Figure 5.16. As observed, solutions 14, 15, and 16 are the ones that represent better solutions than those obtained for the As-Is network across all objectives.

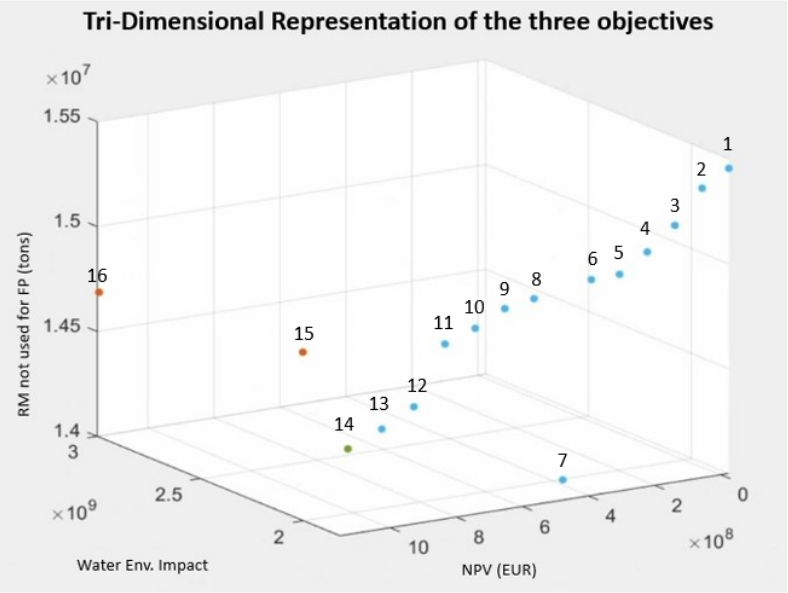

Figure 5.16: Tri-Dimensional Representation of the three objectives.
The solutions highlighted in red and green represent the potential solutions for the To-Be proposal.

Solution 7 is particularly interesting to observe because the values associated with economic performance and water environmental impact follow the trend of the graph; however, this solution stands out for having the lowest value when it comes to waste and resource usage, primarily due to the increased production of FP5.

Based on this study, solution 14 is suggested as a potential network structure that aligns better with the goals intended by companies in the food sector. The selection of this solution is performed according to the company's economic and environmental objectives, based on two criteria:

- The first criterion is that the selected network should represent an improvement in economic performance, with an equal or higher NPV compared to the value for the As-Is solution. As a result, all solutions are excluded, except solutions 14, 15, and 16 (red and green points in figure 5.16).
- The second criterion pertains to the environmental perspective. The proposed network should have the lowest environmental impact in terms of water environmental impact and waste generation. In this context, solution 14 stands out as the one that delivers improved results for both of these objectives, when compared to solutions 15 and 16.

Table 5.17 provides the values related to solution 14 (green) in figure 5.16.

To compare the water consumption for this solution with the previous ones identified during the analysis of the model using a single-objective approach for the To-Be situation, as shown in Figure 5.7, it is verified that the total water consumption over the ten years of operations amounts to 127.316 million cubic meters (M m^3). With this new network structure, there is a substantial reduction of 28% in water consumption over the 10-year period when comparing with the As-Is solution.

Table 5.17: The objective results for the proposed solution in the To-Be context. The improvements obtained with this solution are also presented compared to the optimal values considering the As-Is network.

Objective Function	NPV	Water Environmental Impact	Waste and RM not used for FP
Solution 14	9.97 x 10^8 EUR	2.03 x 10^9	1.43 x 10^7 tons
Improvements	+1.2 %	-41.9 %	-19.6%

Figure 5.17 presents the strategic decisions that lead to these results. The factories used are highlighted in yellow and green, and the suppliers are also identified.

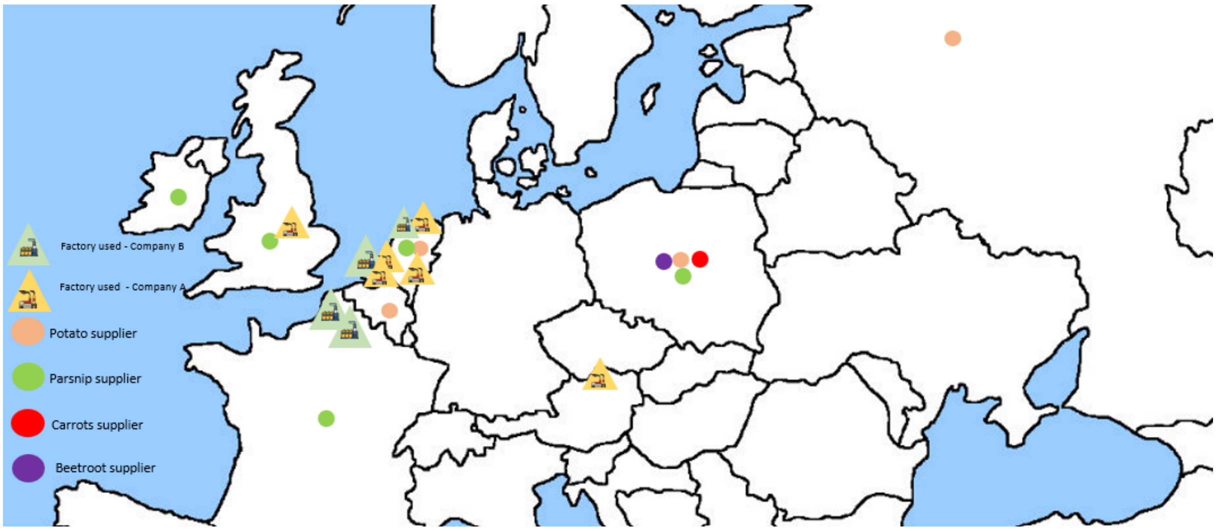

Figure 5.17: Network structure for the To-Be solution proposed.

Table 5.18 presents the proposed FPs to be produced over the next ten years, contributing significantly to the improvements obtained.

Table 5.18: Final Products produced for the proposed solution.

Final product	FP1	FP2	FP3	FP4	FP5	FP6
Proposed Solution	22.9%	25.6%	3.5%	19.7%	25.3%	3.0%

The different FPs presented must be analyzed from the customer's point of view (figure 5.18), as well as from the supplier's point of view (figure 5.19). It is intended to verify that over the 10 years, the availability of different FPs for customers is approximately the same and the RMs needed to produce per year also follow a similar variation. This is important to have stability in operations and contribute to maintaining consistent and reliable production processes.

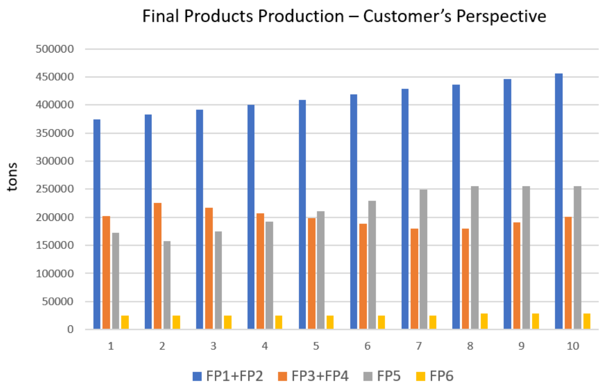

Figure 5.18: Final Products Produced grouped according to the type of cut.

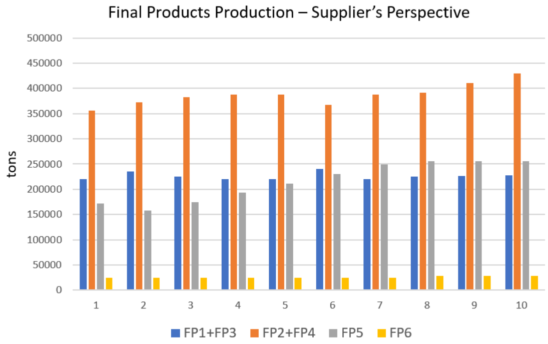

Figure 5.19: Final Products Produced grouped according to the type of RM used.

To compare the As-Is solution with the one to be proposed, the percentages of products lost along the supply chain must be determined. Figure 5.20 and 5.21 represent the resource utilization for the As-Is and To-Be solutions, respectively, and depict the design of waste/loss levels. By suggesting this new network solution, the idea is to decrease the quantity of RMs needed and better optimize resource utilization. Figure 5.21 presents significant improvements when compared with the results presented for the As-Is network. It is verified a reduction of 12% in the amount of tubers that need to be planted to meet the demand, as represented in the section denominated ”Total RM” for both figures 5.20 and 5.21.

The model developed maintains fixed percentages for losses associated with crop activity. Nevertheless, the findings indicate that a reduction in the quantities of RMs required for each factory leads to an overall decrease in losses linked to farmers' activities. Thus, the collaborative reduction of losses both at the point of farmer production and along the supply chain can substantially decrease the quantities that need to be produced to meet the demand. Losses occurring near the suppliers are often attributed to inadequate infrastructure, limited knowledge, or organizational challenges and that is possible to improve for most of the cases.

With the implementation of the new solution, waste in the factories (highlighted in brown in figures 5.20 and 5.21) corresponds to 43% compared to the waste in the previous network, which can be attributed to the integration of technologies aimed at extracting starch from wastewater. The other by-products, such as peels, slivers or flakes, derive from the quantities and types of FPs and the quantities obtained are also lower.

Lastly, near the consumers stage, it is verified an increase in the waste levels, due to the introduction of new products. Estimating this value accurately is complex and different factors are involved, as the correlation between the introduction of new products and waste levels is not necessarily linear. However, even accounting for this potentially pessimistic scenario, it is evident that the overall outcomes remain promising and result in substantial improvements.

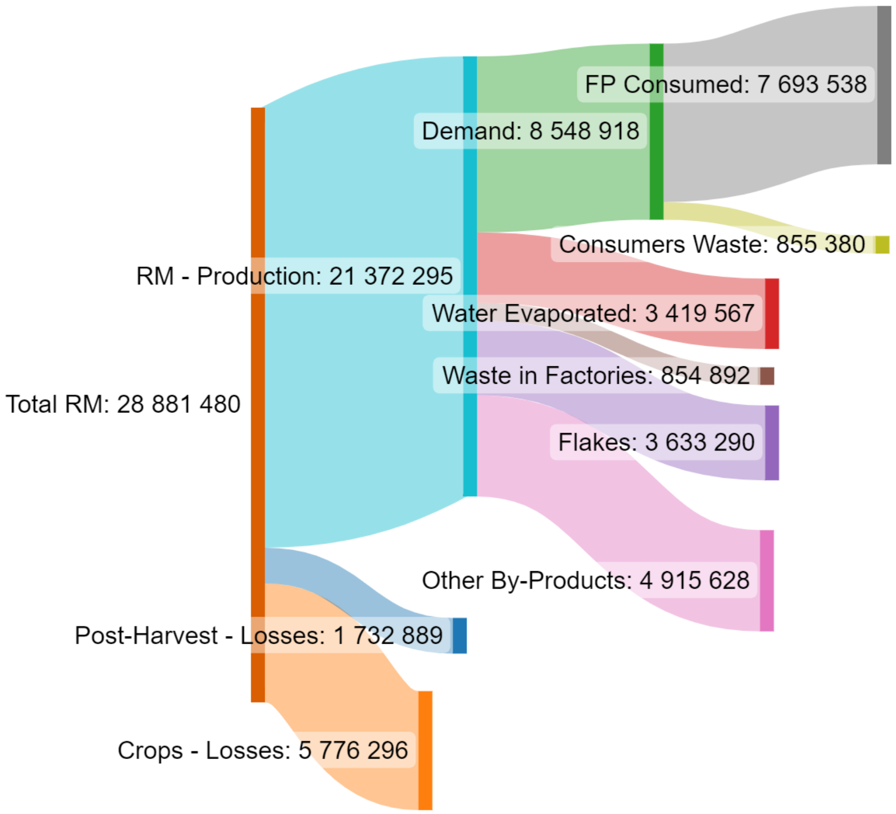

Figure 5.20: Relationship between the overall volume of raw materials (measured in tons) needed to be produced and the amounts that are consumed, representing the real need, for the As-Is solution.

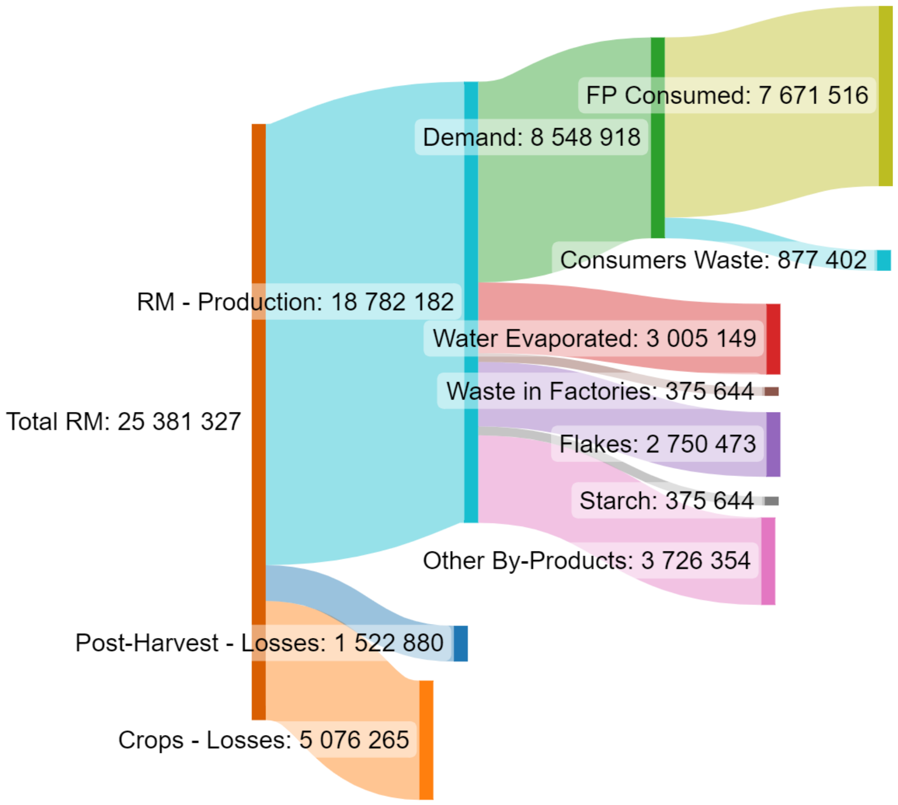

Figure 5.21: Relationship between the overall volume of raw materials (measured in tons) needed to be produced and the amounts that are consumed, representing the real need, for the solution proposed.

Note that the waste considered near the consumer level can be reduced by reducing the portions and providing education about food loss and waste.

The reduction of RMs needed leads to lower water consumption levels as already verified. The proposed solution reduces the water consumption per FPs as well as the total losses along the FSC.

Figure 5.22 presents a comparison of the waste and losses between the network for the As-Is and the proposed solution.

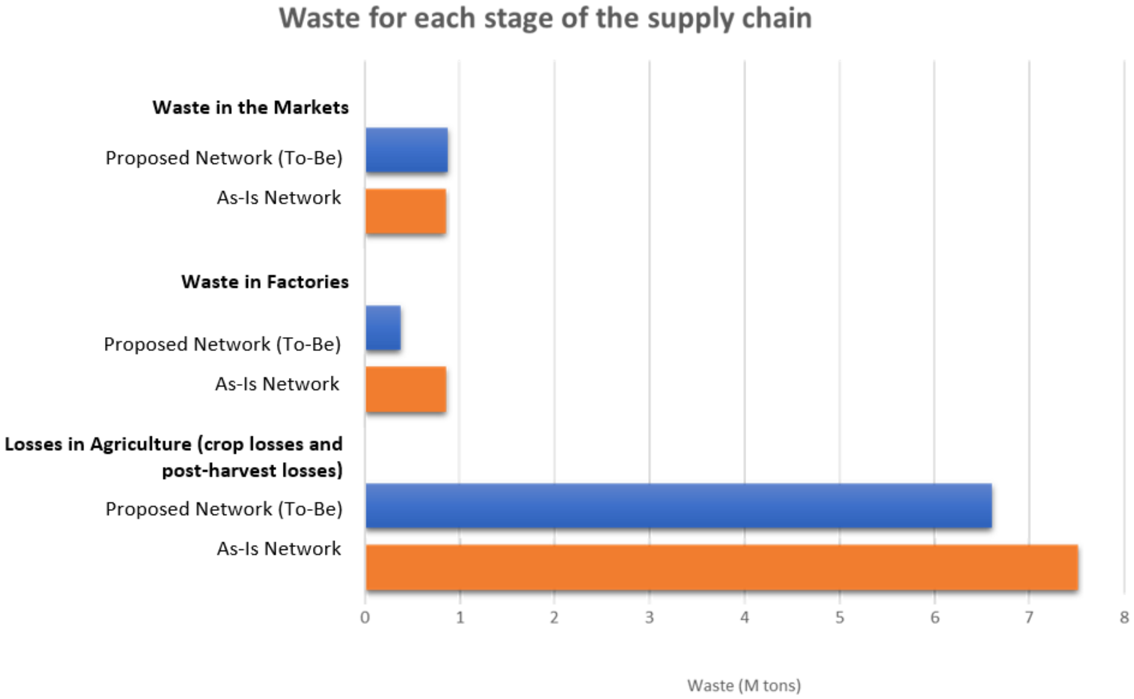

Figure 5.22: Amounts of raw materials wasted or lost along the supply chain.

Observing the results it is clear that by introducing new FPs in the network, the amounts of waste can be reduced during the processing phase and also in the agriculture stage. Note that the proposed network leads to a reduction of 15% in the total waste levels over the 10 years considered. The waste or losses that can be reduced, when converted to nutritional value (in Kcal), is estimated to provide sustenance for 120 630 people over a period of 10 years. That value is calculated using the difference of waste between the As-Is and To-Be solution and then converting it into Kcal, considering that on average 0.1 kg of potatoes is equivalent to 65 Kcal.

Even observing a small increase in the waste levels in the markets, figure 5.23 demonstrates that when converting this waste into water consumption, it is verified a huge decrease compared to the As-Is solution. This occurs due to the overall optimization of water resources along the FSC. Figure 5.23 intends to demonstrate how much water is wasted when wasting food. It is observed that waste near the final consumers, even representing a smaller percentage of the waste along the SC, represents a high water waste. In the case of the To-Be solution, the water associated with waste near the final consumers accounts for 57% of the total water waste. When wasting food in this phase 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 consumed in agriculture, which is minimized by choosing suppliers with lower water footprints and FPs that consume fewer resources to be produced.

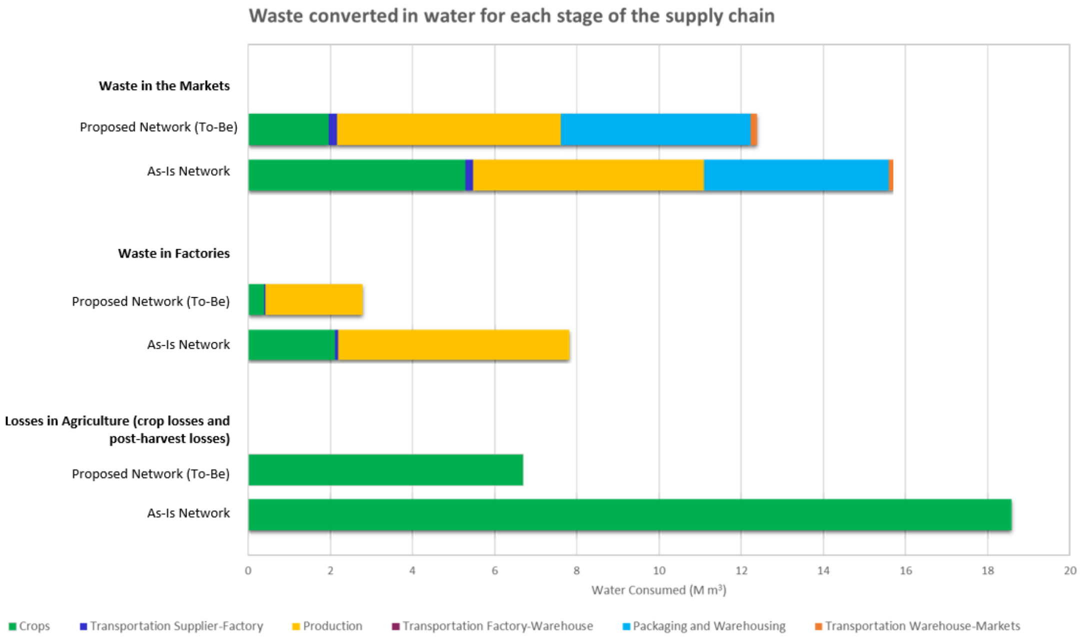

Figure 5.23: Amounts of raw materials wasted or lost converted in water consumption (m^3) along the supply chain.

The total water footprint associated with food losses and waste for the To-Be network accounts for 21 854 128 m^3, while for the As-Is network, the value reaches 42 110 747 m^3, which corresponds to a reduction of 48%. The results shown prove the importance of optimizing all the stages of the SC in order to avoid waste and losses, which leads to more sustainable operations. When assessing waste and losses as a measure to reduce water waste, it is relevant to evaluate all the phases of the SC and identify the most critical activities, in order to define the most relevant stages to be optimized.

Lastly, to evaluate the water resources used per country, an analysis presented in figure 5.24 was performed. According to the scale used, the UK and Austria are the regions with factories that exhibit a lower water stress level, however, the activities in these regions are limited since there is only one factory in each country. On the other side, the Netherlands presents the third lowest water stress level and there are many factories in this area which explains the high water utilization. This geographic location, in this context, can be considered a ”hotspot” due to its high importance for the supply chain. France presents a lower water stress level than Belgium and Poland, which explains the fact that it is one of the locations chosen for production. Finally, Russia, Poland and Ireland are used only as suppliers.

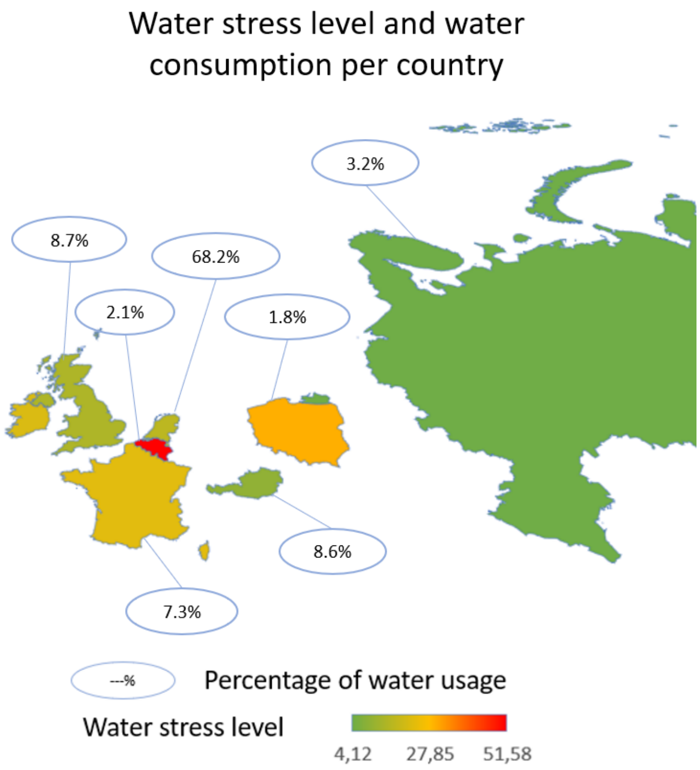

Figure 5.24: Percentage of water consumption over 10 years of operations, by country.

5.3 To-Be Analysis: Stochastic approach considering demand uncertainty

The potato demand is expected to increase over the next 10 years, due to growth in Europe of the business of the fast food chain. One of the frozen potato producers estimates an annual growth of 2.2% per country. However, a period of 10 years is long and can easily be affected by changes in consumption patterns, meaning that the demand can increase more or less than expected or even decrease. Note that a demand decrease is not probable to happen, however, due to instability in Europe nowadays, it is a scenario to be analyzed. The goal is to understand how the profitability and the network decisions would be affected by changes in the expected demand. Thus, a stochastic approach is followed.

For that, different scenarios are defined, which are identified by a new index "sc" that was added to the following decision variables: $X_{m,i,j,t,sc}$, $P_{m,i,j,t,sc}$, $Aux1_{i,t,sc}$. All the constraints were adapted to be in accordance with the scenarios added.

The stochastic economic objective function is given by equations 5.1-5.3 and replaces equations 3.11-3.13.

$$\max \quad NPV = \sum_{sc} prob_{sc} \left(\sum_{t2T} \frac{CF_{t,sc}}{(1+ir)^t} - FCI \right) \tag{5.1}$$

$$CF_{t,sc} = NE_{t,sc}, \qquad \forall t \in T \wedge sc \in SC \tag{5.2}$$

$$
\begin{aligned}
NE_{t,sc} = (1-tr)[& \sum_{(m,t):m2m_{fp}} FPCost_m \sum_{io,id:(m,io,id,t)2F^{INcfp}} X_{m,io,id,t,sc} + \\
& \sum_{(m,t):m2m_{rm}} \sum_{n,g,i:(n,g)2H1^{\wedge}(n,i)2V^{fac\text{-}fp}} P_{n,g,i,t,sc} \cdot BOM^{rm}_{m,n} \cdot Used\_flakes_n \cdot FlakesCost + \\
& \sum_{(t,i):i2i_f} Aux1_{i,t,sc} \cdot starch\_recovered \cdot StarchCost - \\
& \sum_{(m,i,id,t):(m,i,id)2F^{OUTsup}} X_{m,i,id,t,sc} * RMCosts_m - \\
& \sum_{(m,i,id,t):(m,i,id)2F^{INfrm}} X_{m,i,id,t,sc} \cdot d\_sf(i,id) \cdot TCost\_truck - \\
& \sum_{(m,i,id,t):(m,i,id)2F^{INwfp}} X_{m,i,id,t,sc} \cdot d\_fw(i,id) \cdot TCost\_truck - \\
& \sum_{(m,i,id,t):(m,i,id)2F^{INcfp}} X_{m,i,id,t,sc} \cdot d\_wm(i,id) \cdot TCost\_truck - \\
& \sum_{(m,t):m2fp_m} \sum_{(i,id):(m,i,id)2F^{OUTffp}} X_{m,i,id,t,sc} \cdot LaborCost_i \cdot Workers_i / FactoriesCapHour_i - \\
& \sum_{(t,i):i2i_f} Aux1_{i,t,sc} * losses\_potatoe * FactoryCosts - \\
& \sum_{(m,t):m2m_{rm}} Flakes_{m,t,sc} * FlakesCost * FactoryCosts - \\
& \sum_{(m,t):m2m_{fp}} \sum_{io,id:(m,io,id,t)2F^{INcfp}} X_{m,io,id,t,sc} * FPCost_m * FactoryCosts] + tr \cdot DP_t
\end{aligned}
\tag{5.3}
$$

The stochastic objective function related to water environmental impact is given by equations 5.4-5.11 and replaces equations 3.27-3.34.

$$\text{min} \quad Water = \sum_{sc} prob_{sc} \left(SupCons_{sc} + FactoryCons_{sc} + PackWhCon_{sc} + TransCons_{sc} \right) \tag{5.4}$$

$$SupCons_{sc} = \sum_{(m,t):m2m_{rm}} \sum_{i,id:(m,i,id)2F^{OUTsup}} waterfootprint_{(m,i)} * X_{m,i,id,t,sc} * water\_stress_i \tag{5.5}$$

$$FactoryCons_{sc} = \sum_{(i,m,t):(i,m)2V^{fac\text{-}fp}} wateruse_{(m,i)} * \sum_{g:(m,g)2H1} P_{m,g,i,t,sc} * water\_stress_i \tag{5.6}$$

$$PackWhCons_{sc} = \sum_{(m,i,id,t):(m,i,id)2F^{INmfp}} pack\_wh\_cons * X_{m,i,id,t,sc} * water\_stress_i \tag{5.7}$$

$$TransCons_{sc} = SFT_{sc} + FWT_{sc} + WMT_{sc} \tag{5.8}$$

$$SFT_{sc} = \sum_{(m,i,id,t):(m,i,id)2F^{OUTsup}} X_{m,i,id,t,sc} \cdot dist\_sf(i,id) \cdot TransWaterCons \cdot water\_stress_i \tag{5.9}$$

$$FWT_{sc} = \sum_{(m,i,id,t):(m,i,id)2F^{OUTfac}} X_{m,i,id,t,sc} \cdot dist\_fw(i,id) \cdot TransWaterCons \cdot water\_stress_i \tag{5.10}$$

$$WMT_{sc} = \sum_{(m,i,id,t):(m,i,id)2F^{OUTwh}} X_{m,i,id,t,sc} \cdot dist\_wm(i,id) \cdot TransWaterCons \cdot water\_stress_i \tag{5.11}$$

The stochastic objective function related to waste/losses and RMs not used for FPs is given by equations 5.12-5.18 and replaces equations 3.35-3.41.

$$\text{min} \quad W = \sum_{sc} prob_{sc} \left(MWaste_{sc} + BP_{sc} + Flakes_{sc} + FWaste_{sc} - Starch_{sc} + AWaste_{sc} \right) \tag{5.12}$$

$$MWaste_{sc} = \sum_{(i,m,t):(i,m)2V^{m\text{-}fp}} \sum_{io:(m,io,i)2F^{INcfp}} X_{m,io,i,t,sc} * Losses\_Market_{i,m} \tag{5.13}$$

$$BPL_{sc} = \sum_{m,n,g,i,t:(n,g)2H1\wedge m2m_{rm}\wedge(n,i)2F^{OUTffp}} P_{n,g,i,t,sc} * BOM^{rm}_{m,n} * Used\_by_n \tag{5.14}$$

$$Flakes_{sc} = \sum_{m,n,g,i,t:(n,g)2H1\wedge m2m_{rm}\wedge(n,i)2F^{OUTffp}} P_{n,g,i,t,sc} * BOM^{rm}_{m,n} * Used\_flakes_n \tag{5.15}$$

$$FWaste_{sc} = \sum_{m,n,g,i,t:(n,g)2H1\wedge m2m_{rm}\wedge(n,i)2V^{fac\text{-}fp}F^{INcfp}} P_{n,g,i,t,sc} * BOM^{rm}_{m,n} * Losses\_potato \tag{5.16}$$

$$Starch_{sc} = \sum_{t,i:i2i_f} Aux1_{i,t,sc} * starch\_recovered \tag{5.17}$$

$$AWaste_{sc} = \sum_{m,i,id,t:m2m_{rm}\wedge(m,i,id)2F^{OUTsup}} \left[\frac{X_{m,i,id,t,sc}}{1 - Loss\_Agri - Loss\_PostHarv} - X_{m,i,id,t,sc} \right] \tag{5.18}$$

For this analysis, four different scenarios are considered, as presented in figure 5.25.

The model was optimized considering the economic objective and the results obtained are presented in table 5.19 for Case A2 (deterministic), previously analyzed, and Case A3 (stochastic).

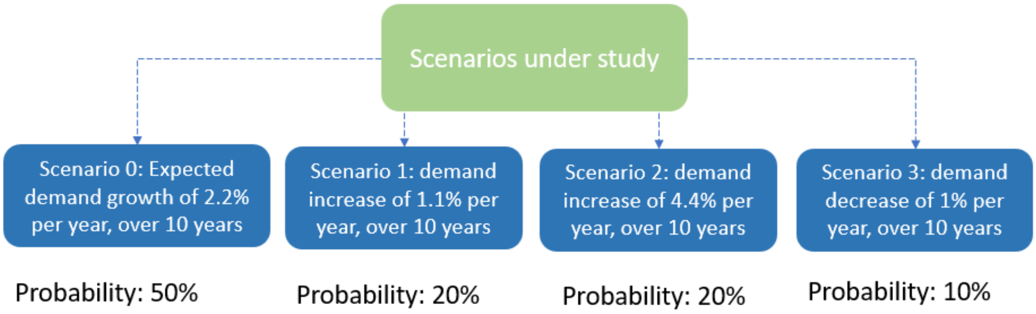

Figure 5.25: Stochastic programming: scenarios under analysis.

Table 5.19: Network parameters for a stochastic (A3) vs deterministic (A2) To-Be approach.

Results	Case A2	Case A3
Raw materials purchased (x 10^6 €)	1814	1812
Total sales (x 10^6 €)	7450	7437
Production Costs (x 10^6 €)	2235	2231
Labor Costs (x 10^6 €)	332	333
Transportation Costs (x 10^6 €)	331.7	330.7
Investment Technology (x 10^6 €)	5.5	5.5
NPV (x 10^6 €)	1154	1151
Water Environmental Impact (x 10^9 €)	2.99	2.98
Minimize RM not used for FP and Waste (x 10^6 €)	14.69	14.66

The results, including uncertainty, 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 associated with these investments is directly proportional to the demand. This relationship exists because these technologies are utilized in accordance with the quantities of final products produced. However, the differences are not significant and reveal that the company continues to be profitable. Moreover, it is observed a small and positive variation related to the water environmental impact as well as the quantities of waste. Note that these impacts are highly correlated with the amounts produced in the factories, which explains the reduction in the values. Overall, it can be concluded that even considering the possibility of having a lower demand, the network structure and the strategic decisions remain unchanged, and therefore, the network is robust in the evaluated scenarios.

Chapter 6

Conclusions

This chapter outlines the main conclusions and achievements of the developed work. Section 6.1 points out the recommendations from the study. Section 6.2 is related to the limitations of the work and includes information for future studies in this field.

6.1 Conclusions and Recommendations

Two main concerns of the food sector are food waste and losses in parallel with water consumption. In particular, agriculture accounts for a significant percentage of global water consumption and represents a sector where improvements can be made to reduce both water environmental impact and losses/waste. The study developed impacts the following sustainable development goals represented in figure 1.1: 6 - clean water and sanitation, 9 - industry, innovation and infrastructure and 12 - responsible consumption and production.

In the literature, some studies emphasize the importance of reducing waste and losses to deal with water scarcity. However, there are no studies presenting tools to guide decision-makers and effectively measure the differences in the water footprint of food losses when considering different supply chain network designs. Moreover, there are no models that evaluate water consumption according to the level of water scarcity in a specific region.

This work proposes a multi-objective mixed integer linear programming model for supply chain design and planning. The model is designed to be applied to different companies and sectors of the food industry by considering the whole supply chain and the impacts associated with each operation, focused on water consumption and usage of resources. Three objectives were defined: maximizing NPV, minimizing water environmental impact, and minimizing food waste/losses and RMs not used for FPs. The water environmental impact is measured by considering the water consumption of a specific activity and the water stress level of the location where it occurs. It allows to:

- Define the locations of each supplier;
- Define the factories being used for production;

- Define a set of products to be produced;
- Define if a specific factory should be or not a candidate to incorporate a specific technology, in this case, to recover starch from water;
- Identify ”hotspots”, considering the water available and water consumption;
- Assess the water footprint associated with food loss or waste at different stages of the supply chain;

To validate the model a case study in the fried potato industry is applied. It is considered the whole SC from crops until the final consumers, measuring the water consumption and waste or losses in agriculture, during the processing phase, transportation, warehousing, packaging and near the final consumers. Different FPs are explored by considering different types of potato cuts and raw materials that lead to different waste quantities and water consumption. Moreover, it is considered an investment in technologies to recover starch from wastewater and reduce waste.

Different networks are obtained by optimizing for each objective, with different 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 centers around the 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, involving the selection of different facilities, suppliers, and various FPs and technologies for starch recovery from wastewater.

The case depends on various parameters that were estimated considering the data available. In order 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.

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 for this problem.

A stochastic approach was developed to deal with the demand uncertainty of each market.

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. This reduction in waste quantities allows for the provision of food to 120 630 people over a period of 10 years. Finally, it is verified that the water footprint associated to food losses and waste is reduced by 21 M m^3, which corresponds to water that was completely wasted in the As-Is solution.

This solution is attributed to the introduction of five new FPs, which include veggie fries made from carrots, beetroot, and parsnips, as well as the selection of different potato suppliers. The new proposal retains only two suppliers, in contrast to the current scenario. It is worth noting that only 48.5% of the FPs are the same as those previously produced. Note that the technology to recover starch is intended to be implemented in all the factories being used. It is observed a reduction of 12% in the raw materials needed to be produced in order to fulfil the demand due to the better usage of resources.

The achieved results are primarily attributed to the careful selection of suppliers and the optimization of the product mix to align with consumption patterns and effectively reduce waste levels and raw material requirements. Furthermore, the adoption of strategies and implementation of technologies to recover and sell by-products has a positive impact on both the economic aspect and waste reduction, leading to a reduction of 15% in the waste levels.

6.2 Limitations and Recommendations for Future Work

The main difficulties found are related to data issues. By extending this study, some limitations could be surpassed to reach even more accurate results.

There is a high degree of uncertainty related to the water footprint of raw materials by region/country. The values can also vary according to specific suppliers in the same country, which should be considered if applied to a real scenario. The same reasoning is applied to pricing and cost data for each geographical location of each entity. Moreover, different suppliers can have different levels of waste and that is an important factor to consider when redesigning the supply chain. Accurate data leads to more precise results when applied to a real-world context where important decisions need to be made, considering relationships with suppliers and possible investments. Finally, the precise location of each supplier is not explicitly incorporated within this model. Obtaining additional data from individual suppliers, instead of considering countries as a whole, could significantly enhance the accuracy of the results. This becomes particularly crucial when addressing the factor of distances, which has been confirmed to exert a substantial influence on transportation costs.

For the case studied, there is no information related to the most relevant industries that can benefit from the derived by-products such as peels, flakes or starch. 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.

The work considers that the introduction of substitute products is well accepted by the customers, however, this should be further analyzed by the marketing teams. These results could be used by companies to inform consumers about the benefits of ”green” products and try to influence their preferences (Taghikhah et al., 2019). Based on Mekonnen and Fulton, 2018, one way to reduce society’s water footprint in relation to food is through dietary changes.

Applying this model, or similar models, in industries whose geographical areas where operations take place are the same, can lead to the overuse of resources. If all sectors exploit the territory similarly, the areas where the water stress level is currently lower would become overloaded in the future. Therefore, the model studied must always be used considering updated data regarding water availability, to allow natural resources (like water basins) time to replenish naturally. It may be advantageous, in some situations, to explore areas with a higher water stress index if the efficiency of water use is greater.

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Appendix A

Water Stress Level Index

To analyze the disparities in the water stress level index across different countries, two graphics were created to facilitate the identification and comparison of the most critical areas within each country's supply chain entities. These graphics serve the purpose of highlighting the variations between the two different scales employed for measuring water stress levels. By visualizing the data in this manner, it becomes easier to pinpoint and understand the discrepancies between regions and their respective water stress levels according to each scale. In figures A.1 and A.2 are presented the two graphics obtained.

Figure A.1: Water Stress level per country in the region where there are possible entities for the supply chain – FAO Index.

Figure A.2: Water Stress level per country in the region where there are possible entities for the supply chain – Aqueduct Index.

It has been observed that there are significant variations in the intensity of water stress when comparing the two different scales of measurement. The choice of one scale over the other can have a substantial impact on the resulting assessments of water stress levels. Therefore, it is crucial to consider this variability and choose the scale that best aligns with the objectives and context of the problem.