

# **Design of the insect-based supply chain in Portugal**

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# Abstract

This project, conducted within the scope of the InsectERA Mobilizing Agenda, focuses on the design and optimization of a supply chain for the emerging insect industry in Portugal. This study addresses the growing demand for sustainable food solutions, in alignment with the United Nations Sustainable Development Goals. Recognizing the insect industry as a promising alternative to mitigate resource scarcity and combat climate change, the developed study presents insect production as an efficient and low environmental impact protein source.

The main objectives of this research include the creation of an optimized supply chain, with the strategic location of new logistic centers, the reduction of operational costs and  $CO_2$  emissions through logistic optimization, and the promotion of sustainability and innovation by integrating circular economy practices in insect production. To this end, a consistent methodology was adopted, including a literature review, mathematical modeling for infrastructure location optimization using MILP, and the analysis of different scenarios considering variations in fixed costs, types of insects and  $CO_2$  emissions constraints.

The results of the optimization of the various scenarios reflect their potential impact on the industry. When only a restriction on the minimum number of factories was imposed, a significant cost reduction was observed, highlighting that the production of the black soldier fly emerged as the most advantageous due to its lower processing costs. Additionally, the scenario that analyzed variable fixed costs revealed that selecting locations with lower fixed costs can provide a substantial reduction in total costs. Lastly, the combined scenario, which integrated the two previous variations, demonstrated that a holistic and integrated approach can effectively balance costs and  $CO_2$  emissions.

In conclusion, this dissertation highlights the feasibility of optimizing the insect industry's supply chain in Portugal, efficiently balancing economic and environmental objectives. The project not only achieved its goals but also offered a clear and comprehensive vision of the challenges and solutions for building an efficient and sustainable supply chain for insect production. This study constitutes a solid foundation for the development of the insect industry in Portugal, aiming for greater solidity and sustainability in the future, promoting innovation and significantly contributing to the global green transition.



# Resumo

Este projeto, realizado no âmbito da Agenda Mobilizadora InsectERA, foca-se na conceção e otimização de uma cadeia de abastecimento para a emergente indústria de insetos em Portugal. Este estudo responde à crescente procura por soluções alimentares sustentáveis, em consonância com os Objetivos de Desenvolvimento Sustentável das Nações Unidas. Reconhecendo a indústria de insetos como uma alternativa promissora para mitigar a escassez de recursos e combater as alterações climáticas, o estudo desenvolvido apresenta a produção de insetos como uma fonte de proteína eficiente e de baixo impacto ambiental.

Os principais objetivos desta investigação incluem a criação de uma cadeia de abastecimento otimizada, com a localização estratégica de novos centros logísticos, a redução dos custos operacionais e das emissões de  $CO_2$ , através da otimização logística, e a promoção da sustentabilidade e inovação, integrando práticas de economia circular na produção de insetos. Para tal, foi adoptada uma metodologia consistente que incluiu a revisão da literatura, a modelação matemática para optimização da localização de infraestruturas utilizando programação linear inteira mista (MILP) e a análise de diferentes cenários que consideraram variações nos custos fixos, tipos de insectos e restrições de emissões de  $CO_2$ .

Os resultados da optimização dos vários cenários refletem o seu potencial impacto na indústria. Quando imposta apenas uma restrição sobre o número mínimo de fábricas, observou-se uma redução significativa nos custos, salientando que a produção da mosca soldado negro emergiu como a mais vantajosa devido aos seus menores custos de processamento. Adicionalmente, o cenário que analisou custos fixos variáveis revelou que a seleção de locais com custos fixos mais baixos pode proporcionar uma redução substancial dos custos totais. Por último, o cenário combinado, que integrou as duas variações anteriores, demonstrou que uma abordagem holística e integrada pode equilibrar eficazmente os custos e as emissões de  $CO_2$ .

Em conclusão, esta dissertação salienta a viabilidade de otimizar a cadeia de abastecimento da indústria de insetos em Portugal, equilibrando de forma eficiente objetivos económicos e ambientais. O projeto não só alcançou os seus objetivos, como também ofereceu uma visão clara e abrangente dos desafios e soluções para a construção de uma cadeia de abastecimento eficiente e sustentável para a produção de insetos. Este estudo constitui uma base sólida para o desenvolvimento da indústria de insetos em Portugal para alcançar maior solidez e sustentabilidade no futuro, promovendo a inovação e contribuindo significativamente para a transição verde global.



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*"Sustainability is no longer about doing less harm. It's about doing more good."*

Jochen Zeitz



# Contents

|          |                                                                                                                       |           |
|----------|-----------------------------------------------------------------------------------------------------------------------|-----------|
| <b>1</b> | <b>Introduction</b>                                                                                                   | <b>1</b>  |
| 1.1      | Project framework and motivations . . . . .                                                                           | 1         |
| 1.2      | The InsectERA Mobilizing Agenda . . . . .                                                                             | 2         |
| 1.3      | Project objectives . . . . .                                                                                          | 3         |
| 1.4      | Project methodology . . . . .                                                                                         | 4         |
| 1.5      | Dissertation structure . . . . .                                                                                      | 4         |
| <b>2</b> | <b>Literature review</b>                                                                                              | <b>5</b>  |
| 2.1      | Insect-based industry supply chains . . . . .                                                                         | 5         |
| 2.1.1    | Legal context and evolution . . . . .                                                                                 | 7         |
| 2.1.2    | Sustainability application . . . . .                                                                                  | 8         |
| 2.1.3    | Insect industry in Portugal . . . . .                                                                                 | 9         |
| 2.2      | Network design and optimization . . . . .                                                                             | 10        |
| 2.2.1    | Models characterization and approaches . . . . .                                                                      | 11        |
| 2.2.2    | Location problems in the insect-based supply chain . . . . .                                                          | 14        |
| <b>3</b> | <b>Problem description and modeling</b>                                                                               | <b>17</b> |
| 3.1      | Inputs definition and description . . . . .                                                                           | 17        |
| 3.2      | Objective functions . . . . .                                                                                         | 21        |
| 3.3      | Constraints . . . . .                                                                                                 | 23        |
| <b>4</b> | <b>Methodology</b>                                                                                                    | <b>25</b> |
| <b>5</b> | <b>Results and discussion</b>                                                                                         | <b>29</b> |
| 5.1      | Baseline scenario . . . . .                                                                                           | 29        |
| 5.2      | Scenario with only one restriction related to the minimum number of facilities . .                                    | 31        |
| 5.3      | Scenario with different fixed costs . . . . .                                                                         | 33        |
| 5.4      | Scenario with only one restriction related to the minimum number of facilities and<br>different fixed costs . . . . . | 36        |
| 5.5      | Different scenarios comparison . . . . .                                                                              | 39        |
| <b>6</b> | <b>Conclusion</b>                                                                                                     | <b>41</b> |
|          | <b>References</b>                                                                                                     | <b>43</b> |
|          | <b>Contribution to the SDGs</b>                                                                                       | <b>47</b> |
| <b>A</b> | <b>Input Data</b>                                                                                                     | <b>49</b> |
| <b>B</b> | <b>Results</b>                                                                                                        | <b>61</b> |



# Acronyms and Symbols

|          |                                           |
|----------|-------------------------------------------|
| AUGMECON | Augmented $\varepsilon$ -Constraint       |
| BCU      | Bioconversion Unit                        |
| BSFL     | Black Soldier Fly Larvae                  |
| CAP      | Common Agricultural Policy                |
| CR       | Conversion Ratio                          |
| DST      | Decision Support Tool                     |
| EEA      | European Environment Agency               |
| EFSA     | European Food Safety Authority            |
| EU       | European Union                            |
| FWP      | Fair Wage Potential                       |
| IP       | Integer Programming                       |
| LP       | Linear Programming                        |
| LS       | Labor Safety                              |
| MILP     | Mixed-Integer Linear Programming          |
| MOMP     | MultiObjective Mathematical Programming   |
| NFR      | Novel Foods Regulation                    |
| NSGA-II  | Nondominated Sorting Genetic Algorithm II |
| RRP      | Recovery and Resilience Plan              |
| SCND     | Supply Chain Network Design               |
| SDG      | Sustainable Development Goal              |



# List of Figures

|     |                                                                                                                                                     |    |
|-----|-----------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 1.1 | InsectERA Agenda axes . . . . .                                                                                                                     | 3  |
| 2.1 | Entogreen's process . . . . .                                                                                                                       | 9  |
| 2.2 | Distribution of insect production companies in Portugal . . . . .                                                                                   | 11 |
| 2.3 | Facility location problem representation . . . . .                                                                                                  | 12 |
| 3.1 | Inputs from facilities . . . . .                                                                                                                    | 18 |
| 3.2 | Inputs from suppliers . . . . .                                                                                                                     | 18 |
| 3.3 | Emissions of $CO_2$ for different velocities . . . . .                                                                                              | 23 |
| 4.1 | Suppliers and facilities locations distribution . . . . .                                                                                           | 26 |
| 5.1 | Pareto Curve for baseline scenario . . . . .                                                                                                        | 31 |
| 5.2 | Distribution of suppliers and facilities for the first and last iterations in the baseline scenario . . . . .                                       | 32 |
| 5.3 | Pareto Curve for scenario with one restriction . . . . .                                                                                            | 33 |
| 5.4 | Distribution of suppliers and facilities for the first and last iterations in the scenario with one restriction . . . . .                           | 34 |
| 5.5 | Percentage of different costs . . . . .                                                                                                             | 34 |
| 5.6 | Pareto Curve for scenario with different fixed costs . . . . .                                                                                      | 35 |
| 5.7 | Distribution of suppliers and facilities for the first and last iterations in the scenario with different fixed costs . . . . .                     | 37 |
| 5.8 | Pareto Curve for scenario with one restriction and different fixed costs . . . . .                                                                  | 37 |
| 5.9 | Distribution of suppliers and facilities for the first and last iterations in the scenario with one restriction and different fixed costs . . . . . | 39 |



# List of Tables

|      |                                                                                                                              |    |
|------|------------------------------------------------------------------------------------------------------------------------------|----|
| 4.1  | Payoff table representation . . . . .                                                                                        | 27 |
| 5.1  | Payoff table representation for baseline scenario . . . . .                                                                  | 30 |
| 5.2  | Facilities constructed for the different iterations in the baseline scenario . . . . .                                       | 31 |
| 5.3  | Payoff table representation for scenario with one restriction . . . . .                                                      | 32 |
| 5.4  | Facilities constructed for the different iterations in the scenario with one restriction . . . . .                           | 33 |
| 5.5  | Payoff table representation for scenario with different fixed costs . . . . .                                                | 35 |
| 5.6  | Facilities constructed for the different iterations in the scenario with different fixed costs . . . . .                     | 36 |
| 5.7  | Payoff table representation for scenario with one restriction and different fixed costs . . . . .                            | 36 |
| 5.8  | Facilities constructed for the different iterations in the scenario with one restriction and different fixed costs . . . . . | 38 |
| 5.9  | Range of costs for the different scenarios . . . . .                                                                         | 39 |
| 5.10 | Range of emissions for the different scenarios . . . . .                                                                     | 40 |
| A.1  | Velocities of trucks for the different locations . . . . .                                                                   | 49 |
| A.2  | Possible black soldier fly facilities . . . . .                                                                              | 50 |
| A.3  | Possible mealworm facilities . . . . .                                                                                       | 50 |
| A.4  | Possible domesticus cricket facilities . . . . .                                                                             | 51 |
| A.5  | Possible suppliers . . . . .                                                                                                 | 52 |
| A.6  | Relation matrix between the different raw materials and their types . . . . .                                                | 59 |
| A.7  | Conversion ratios of the different raw materials for the different insects . . . . .                                         | 59 |
| A.8  | Fixed costs variation with the districts . . . . .                                                                           | 60 |
| B.1  | Costs evolution for the different scenarios . . . . .                                                                        | 61 |
| B.2  | Emissions evolution for the different scenarios . . . . .                                                                    | 61 |



# Chapter 1

## Introduction

This chapter introduces the purpose of this dissertation and elucidates the significance of the work undertaken for the insect industry in Portugal. Funded by the InsectERA Mobilizing Agenda, the work and primary objectives of this Agenda will be described. Subsequently, a focus will be placed on the specific goals of the developed project and the methodology adopted throughout the entire research period. Finally, the structure of the dissertation will be explained, detailing the contents of the subsequent chapters.

### 1.1 Project framework and motivations

This project, in collaboration with the InsectERA Mobilizing Agenda, is directly linked to the insect industry in Portugal. As an emerging industry both nationally and globally (Liang et al., 2024), it is imperative to establish protocols and procedures that contribute to its development. The project is entirely concentrated on the supply chain of this industry, with the primary objective of its creation, considering the available raw materials and identifying new locations for logistical hotspots.

The benefits of insects for human and animal nutrition are widely acknowledged (Lin et al., 2023), and there is extensive documentation on the subject. However, documentation concerning logistics, specifically the optimization of new factories and logistics center locations, is limited, which motivated the creation of this InsectERA project. This work provides a clear vision of the main challenges in constructing a supply chain and how these should be addressed in its optimization, focusing on transactions between suppliers and the producer entity, a critical point for companies producing insects in Portugal.

The insect industry is in constant growth (Sogari et al., 2023), with an expected production of about 260,000 tons of insect-based products by 2030 in the European Union (Żuk Gołaszewska et al., 2022). Therefore, advancing logistics is crucial to optimize the construction of new logistical hotspots, reduce transaction costs and mitigate environmental damage, aligning with the United Nations sustainable development goals (United Nations, 2015).

## 1.2 The InsectERA Mobilizing Agenda

The Mobilizing Agendas for Business Innovation, part of the Recovery and Resilience Plan (RRP), emerged to consolidate and expand synergies between the business sector and the scientific and technological system in Portugal, contributing to increase competitiveness and resilience of the Portuguese economy, based on research and development, innovation, diversification and specialization of the productive structure.

The InsectERA Mobilizing Agenda brings together various entities to explore the insect industry and its potential as an industrial tool and bioindustrial solution. Innovation is one of the pillars of the InsectERA Agenda, encompassing everything from manufacturing to product commercialization, utilizing advanced production methods.

The InsectERA Agenda offers alternative nutritional solutions to meet the new needs of the sector, such as the growing world population, climate change and food waste. Thus, it contributes to the green transition towards environmental sustainability, based on a circular economy.

The development of the InsectERA Agenda is scheduled for 2023 to 2025, with objectives such as creating a new value-added productive sector, developing 100 new products, processes, and services, creating 140 new jobs, generating new value chains and installing 4 bioindustrial units, 2 innovation and development centers and 1 logistic center.

Figure 1.1 identifies some axes of the InsectERA Agenda. Among the vertical axes, we have:

- **Infod:** Utilizing insects as a nutritional source for human consumption;
- **Infeed:** Utilizing insects as a nutritional source for more sustainable and locally-sourced animal feed;
- **Inindustry:** Utilizing insect-derived products for the production of new raw materials;
- **Inbiorremediation:** Utilizing insects as a bioremediation tool and solution for environmental challenges, such as the elimination of livestock effluents and urban organic waste.

In terms of transversal axes, it is important to highlight:

- **Infrass:** Creating a high-quality organic fertilizer composed of insect excreta and decomposed material;
- **One Health:** Conducting risk assessments and quality and safety studies of different products, considering their impact on human, animal and environmental health and the high risk if not correctly processed (Rivas-Navia et al., 2023);
- **IN2MARKET:** Conducting an extensive study of the entire sector to ensure the market entry of new products, addressing legal aspects, consumer level, life cycle assessment, dissemination, human resources training and exploitation.

Finally, in terms of horizontal axes, the Agenda considers the following:

- **Raw materials and Production:** Using insects as a healthy and sustainable alternative nutritional source in 15 new product lines for human consumption;
- **IN 4.0:** Using insects as a nutritional source in more sustainable and locally sourced animal feed with 8 new product lines (feeds).



Figure 1.1: InsectERA Agenda axes

### 1.3 Project objectives

The objective of this project aligns with the horizontal axis "Raw materials and Production", as the focus is on optimizing the construction of new facilities based on the available set of suppliers.

The project has two specific objectives:

1. Develop a mathematical model to determine the optimal locations for logistics hotspots in the insect-based supply chain;
2. Analyze solutions considering different sustainability goals.

Through the formulation of the mathematical model, different solutions for potential facility locations are identified, considering various scenarios and changes in the problem's constraints and objective functions, addressing both economic aspects (acquisition, transportation, processing and fixed costs) and environmental aspects ( $CO_2$  emissions associated with raw material transportation).

The model focuses on transactions between raw material suppliers and potential insect production factory locations. Based on the available data, several scenarios were created, allowing an evaluation of the influence of different parameters on the final solution.

## 1.4 Project methodology

This project is divided into three main phases: literature review, optimization model construction and model testing and result analysis.

Initially, a literature review on existing optimization models for the insect industry supply chain was conducted, along with an analysis of insect-producing companies in Portugal and the different types of insects to be explored, including the black soldier fly (*Hermetia illucens*), the mealworm (*Tenebrio molitor*) and the house cricket (*Acheta domesticus*). Subsequently, a literature review on network design models and location problems was carried out, exploring the best methods and techniques for model formulation and interpretation.

The optimization model was then developed, incorporating all relevant decision variables and parameters. Through imposed constraints and objective functions, an optimization model for the problem was obtained, creating different scenarios to evaluate the influence of certain parameters on the final results.

Lastly, random data were generated to test the model, due to the absence of concrete and real data. These data were tested in different scenarios and objective functions, confirming the model's feasibility and allowing a sensitivity analysis regarding the influence of different parameters on the results obtained.

## 1.5 Dissertation structure

This dissertation comprises six chapters. Following this introductory chapter, Chapter 2 focuses on the literature review, which provides context for the insect industry and network design problems and optimization and introduces several existing models.

Chapter 3 will detail the problem more comprehensively and describe the modeling approach adopted for its resolution. Chapter 4 explains the model's specifications and how the methodology is empirically applied to this project and Chapter 5 presents the results obtained from the optimization model across different scenarios, including a comparative analysis of these scenarios.

Finally, Chapter 6 outlines the conclusions and key findings of the research. It also addresses the limitations of the current model and proposes suggestions for future work.

## Chapter 2

# Literature review

Before introducing the model, it is important to provide a theoretical context for the problem. Therefore, this chapter will include a review of the existing literature on the insect industry, focusing on its evolution and legal framework. Given that a sustainable component will be incorporated into the model, it is important to highlight the benefits of this industry in this area. An overview of the insect industry in Portugal will also be presented.

Additionally, a literature review on optimization models for location problems and their possible approaches will be conducted. The models used as the basis for the development of the model presented in this dissertation, along with their main differences, will also be discussed.

### 2.1 Insect-based industry supply chains

The global population is projected to increase by 20% over the next 30 years, significantly raising the demand for food and other essential resources (FAO, 2019). This surge in population will need a 50% increase in protein for human consumption, expected to reach approximately 280 million tonnes by 2050 (OECD/FAO, 2020). Currently, the demand for animal feed is anticipated to double, placing immense pressure on existing agricultural systems (Searchinger et al., 2019). Traditional livestock farming, which is resource-intensive, will struggle to meet these demands due to its significant requirements for land, water and feed, and its substantial contribution to greenhouse gas emissions (FAO, 2020).

As stated by Entogreen (2021), the agro-food sector faces two significant challenges: soil desertification, which necessitates an increasing input of nutrients, and dependence on imported nutritional sources for animal feed. Additionally, food waste poses a substantial challenge, leading to inefficiencies in natural resource management and nutrient loss throughout the value chain.

Food insecurity is exacerbated by climate change, extreme weather events such as prolonged droughts and floods, global supply chain disruptions and geopolitical conflicts. In particular, growing populations in low and middle income countries (LMICs) will require more accessible, affordable and sustainable nutrition. Scaling up traditional agriculture and livestock production is not a

sustainable solution, as these industries contribute significantly to the climate crisis (Hazarika and Kalita, 2023).

Insects offer a promising alternative to conventional protein sources due to their high feed conversion efficiency, rapid growth rates and ability to be reared on organic waste (Dobermann et al., 2017). For instance, insects like the black soldier fly, mealworm and house cricket are rich in protein and can be produced sustainably with a lower environmental footprint compared to traditional livestock (van Huis, 2020). Insect farming aligns with the principles of a circular economy, where waste is minimized and resources are efficiently recycled, thus contributing to the sustainability of food systems (Sogari et al., 2019).

Madau et al. (2020) stated that despite their potential, harvested insects currently represent 92% of the total world insect supply, with semi-domesticated insects accounting for 6% and only 2% of insects being farmed directly for human consumption. This indicates a significant opportunity for growth in farmed insect production to meet rising protein demands sustainably.

Logistics service providers play a crucial role in supporting the insect-based industry by ensuring suitable levels of service to customers. This involves optimizing facility location layouts, minimizing distances from suppliers to facilities, meeting time requirements for delivering goods, ensuring the capability of facilities to support customer demands and enhancing the connectivity of transportation routes (Xifeng et al., 2013).

Moreover, the type of feed selected (e.g., vegetable rests, compound feed, food waste) and the properties of the selected feed (e.g., nutrient content, moisture content) greatly influence the performance and environmental impact of insect production systems (Smetana et al., 2021). Efficient feed utilization is the key to maximize the sustainable benefits of insect farming.

The economic potential of the insect-based industry is also noteworthy (Halloran et al., 2018). Insect farming can generate employment opportunities, especially in rural areas, and contribute to economic development by creating new markets for insect-derived products. Additionally, insects can be used in various applications beyond food and feed, including pharmaceuticals, cosmetics, and bioplastics, further expanding their market potential (van Huis, 2020).

Despite the clear benefits, the insect-based industry faces challenges such as regulatory barriers, consumer acceptance and the need for scalable production methods (Acosta-Estrada et al., 2021). Nilapornkul and Aoithongdee (2019) emphasize the need for educational campaigns and marketing strategies to overcome consumer reluctance and promote insect-based foods as a viable protein source. Educating consumers about the nutritional benefits and sustainability advantages of insect-based products is essential for increasing their acceptance and market penetration (Hazarika and Kalita, 2023).

Ensuring the safety and quality of insect-based foods is critical for building consumer trust. The safety of insects as food depends on various factors, including the species, rearing environment, feed and processing methods (Hazarika and Kalita, 2023). Adhering to strict safety standards and regulatory compliance is necessary to ensure the quality and safety of insect-based products (Madau et al., 2020). This involves regular monitoring and testing to prevent contamination and ensure that the products meet the required health standards (Spatola et al., 2024).

With increasing recognition of the environmental and economic benefits, along with supportive regulatory frameworks, the industry is poised for growth. As consumer awareness and acceptance improve, the demand for insect-based products is likely to increase, paving the way for a more sustainable food system (Alhujaili et al., 2023).

### 2.1.1 Legal context and evolution

The legal framework governing the insect-based industry in Europe is critical for ensuring the safety, quality and sustainability of insect-derived products. The European Union (EU) has established a series of regulations to facilitate the growth of this sector while addressing safety and environmental concerns. Since 2018, insects have been included within the scope of the Novel Foods Regulation (NFR) 2015/2283, which mandates that insect-based food products undergo a safety assessment by the European Food Safety Authority (EFSA) before they can be marketed (Lähteenmäki-Uutela et al., 2021). Applications for various insect species such as black soldier fly (*Hermetia illucens*), yellow mealworm (*Tenebrio molitor*) and house cricket (*Acheta domestica*) were under review, with the first safety assessments expected in the next years as stated by Lähteenmäki-Uutela et al. (2021). This regulation ensures that insect-based foods meet stringent health standards and are safe for consumption (Madau et al., 2020).

It also removed the requirement for insect rearing facilities to comply with traditional slaughterhouse regulations, recognizing the unique nature of insect farming (Lähteenmäki-Uutela et al., 2021). This regulation marked a significant shift in the legal landscape, enabling the broader use of insect proteins in animal feed and addressing environmental sustainability (Spatola et al., 2024).

The EU's commitment to sustainability is evident in its integration of the Agenda 2030 for Sustainable Development and ongoing reforms of the Common Agricultural Policy (CAP). These reforms aim to promote environmentally, socially and economically sustainable agricultural practices (Madau et al., 2020). The CAP reforms, in particular, are designed to support agricultural development in a manner that is aligned with sustainability goals, thereby influencing both the production and consumption of food within the EU (Entogreen, 2021).

Despite these advancements, there are still significant legislative barriers that need to be addressed to fully unlock the potential of the insect industry. For example, substrate options for rearing insects remain restricted to materials that are also permitted for other livestock species, limiting the industry's flexibility and scalability (Lähteenmäki-Uutela et al., 2021). Comprehensive legislation that supports the use of diverse organic substrates in insect farming is necessary for the industry's expansion (Hazarika and Kalita, 2023) and insects, being products of animal origin, are equally subject to measures to prevent, eradicate and monitor certain encephalopathies transmissible spongiform diseases (Costa et al., 2018).

The legal framework also plays a critical role in addressing global food security challenges (Hazarika and Kalita, 2023). Climate change, extreme weather events and geopolitical conflicts have highlighted the need for resilient and sustainable food systems as stated by Costa et al. (2018). Insects, with their low resource requirements and high nutritional value, offer a viable solution to these challenges. The ability to produce high-quality protein with minimal environmental impact

positions insects as a key component in strategies aimed at mitigating food insecurity (Susinchain, 2022).

### 2.1.2 Sustainability application

Insect farming presents numerous sustainability benefits compared to traditional livestock farming, making it a promising alternative in the context of global food security and environmental sustainability. Traditional livestock farming is a significant contributor to greenhouse gas emissions, with the meat industry alone responsible for over 7,1 billion tonnes  $CO_2$  equivalent annually, representing 14,5% of all anthropogenic greenhouse gas emissions (Hazarika and Kalita, 2023). In contrast, insect farming has a much lower carbon footprint, offering a more sustainable protein source (Madau et al., 2020). This reduced environmental impact is critical for addressing climate change and reducing the ecological footprint of food production (Entogreen, 2021).

Entogreen's circular economy model is a prime example of how insect farming can contribute to sustainability. Entogreen uses agro-industrial by-products to nourish insect larvae, which are then processed to produce insect protein, oil and organic fertilizer (Entogreen, 2021). This approach not only mitigates food waste but also reduces dependency on imported nutritional sources (Madau et al., 2020). By converting waste into valuable resources, Entogreen exemplifies the principles of a circular economy, enhancing the sustainability of agricultural practices.

Insect farming plays a crucial role in promoting a zero-waste economy. Insects can recycle various types of food and organic waste, converting them into high-quality protein and other valuable products (Madau et al., 2020). This capability not only improves feed and food quality but also enhances productivity and sustainability within the food supply chain (Smetana et al., 2021). By reducing waste and promoting resource efficiency, insect farming supports the broader goals of sustainable development (Susinchain, 2022).

Insects are highly efficient in converting feed into protein, with feed Conversion Ratio (CR)'s that are significantly better than those of traditional livestock (Hazarika and Kalita, 2023). They grow quickly and produce more offspring, making them an efficient and sustainable protein source. This efficiency is particularly important for meeting the nutritional needs of growing populations in low and middle income countries without exacerbating environmental degradation (Madau et al., 2020). Insects can be farmed on organic waste, further enhancing their sustainability credentials (Smetana et al., 2021).

Insect farming requires fewer resources such as land, water, and feed compared to conventional livestock farming. This reduced resource demand makes insect farming a more sustainable option, especially in regions facing resource scarcity (Hazarika and Kalita, 2023). For example, Smetana et al. (2021) stated that the water footprint of insect farming is significantly lower, making it a viable solution in water-stressed areas. The feed used in insect farming can also be derived from organic waste, reducing the competition for arable land and enhancing the sustainability of the food production system.

The insect farming industry offers notable energy efficiency advantages compared to traditional livestock production. Insects require less energy for thermoregulation since they are ectothermic, relying on ambient temperature, unlike endothermic animals that need substantial energy to maintain their body temperature (Oonincx and de Boer, 2012). Furthermore, insect farming often utilizes organic waste and by-products as feed, significantly reducing the energy needed for feed production (Madau et al., 2020). The vertical farming model used by companies also enhances energy efficiency by optimizing space and resource use and incorporating AI to monitor and optimize breeding conditions can further reduce energy consumption (Rustici, 2023). This combination of lower feed requirements, reduced need for heating and advanced technological integration makes insect farming a highly energy-efficient and sustainable alternative to conventional animal farming (Pells, 2023).

### 2.1.3 Insect industry in Portugal

Portugal's insect industry is making significant advancements, driven by innovative companies such as Entogreen, whose process can be seen in Figure 2.1. In that way, by using agro-industrial by-products to nourish insect larvae, Entogreen converts waste into valuable products such as insect protein, oil and organic fertilizer. This approach addresses both food waste and the need for sustainable nutrient sources, positioning Entogreen as a leader in sustainable agricultural practices.

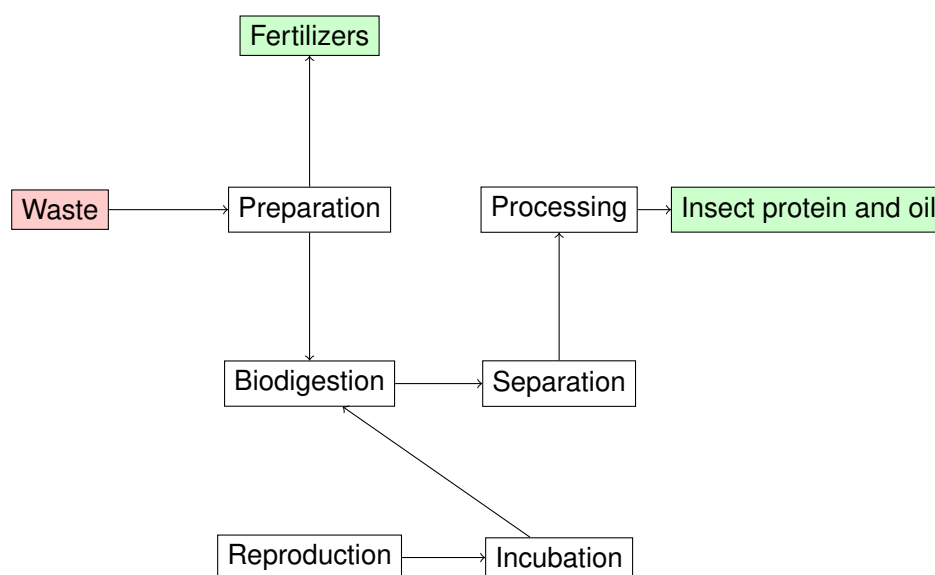


Figure 2.1: Entogreen's process

Entogreen, located in Santarém, plans to establish a facility capable of converting 3000 tons of vegetable by-products per month, producing 750 tons of organic fertilizer, 214 tons of insect protein and 42 tons of insect oil. The establishment of such facilities is crucial for scaling up production and meeting market demands (Hazarika and Kalita, 2023). By creating a sustainable and scalable model, Entogreen (2021) aims to enhance the economic viability and sustainability of the insect industry in Portugal.

The insect industry in Portugal is rapidly growing, driven by several innovative companies and strategic initiatives. Portugal Bugs is a pioneer in the creation and processing of insects for human and animal consumption. By developing products such as protein bars, pasta, chocolates and bread that incorporate insect flour, the company promotes sustainable and nutritionally rich alternatives, helping to reduce the environmental footprint of traditional food production (Agrozapp, 2024).

Additionally, Thunder Foods SA has announced a €13 million investment to build the largest insect-derived food production facility in Santarém, set to begin operations in 2026. This facility will have the capacity to produce tens of tons of products per month, marking a significant step towards the industrialization and scalability of insect-based food production, thereby promoting large-scale food sustainability (Jornal de Abrantes, 2024).

Companies like Aki à Bixo and The Cricket Farming Co are also vital to the industry, focusing on the creation of insects for animal and human consumption, respectively. Aki à Bixo specializes in *Tenebrio*, *Zophoba*, crickets and locusts, maintaining high standards of hygiene and safety. This company significantly contributes to the animal feed market by offering sustainable and high-quality protein alternatives. (Portugal Insect, 2024). The Cricket Farming Co, on the other hand, is dedicated to producing domestic crickets (*Acheta Domestica*) for human consumption, noted for their high nutritional profile and sustainability.

Projects such as CircleFly by The Tomorrow Company in Madeira and Douro Valley Bugs are also essential to the industry. CircleFly values organic waste by producing Black Soldier Fly Larvae (BSFL) for animal feed, promoting a circular economy and resource sustainability. Douro Valley Bugs focuses on the production of tenebrio for animal feed, providing protein and fat-rich food with low environmental impact, essential for healthy animal growth. (Portugal Insect, 2024).

Portugal Insect (2024), founded in May 2018, is an association that brings together insect producers and processors in Portugal. Working directly with national official entities, it promotes the use of insects in animal and human food, facilitating the coordinated growth of the sector and ensuring that technical and scientific developments have a lasting impact.

Figure 2.2 represents the distribution of insect production companies that are transforming Portugal into an emerging leader in the insect production industry, contributing to sustainable and innovative food solutions.

Niyonsaba et al. (2021) provides insights into the economic aspects of insect farming in Portugal. It highlights the importance of operational efficiency and the circular economy in enhancing profitability. By reducing production costs and improving sustainability, insect farming can become a competitive and profitable industry. Various strategies to enhance profitability include optimizing production processes, improving feed efficiency and exploring new market opportunities (Entogreen, 2021).

## 2.2 Network design and optimization

This section will address the different approaches to an optimization problem, specifically network design. Additionally, some models found in the literature that served as the basis for the creation

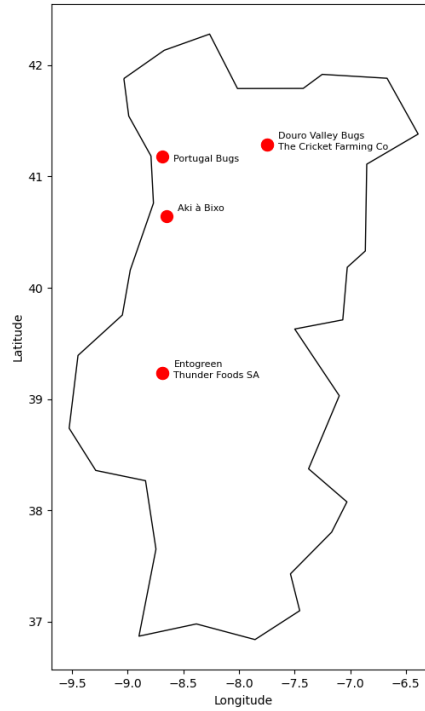


Figure 2.2: Distribution of insect production companies in Portugal

of the model presented in this dissertation for solving the problem will be discussed, along with the main differences between them and the created model.

### 2.2.1 Models characterization and approaches

Supply chain optimization is a complex field that involves various modelling approaches to enhance efficiency and sustainability. These models can be broadly categorized based on their objectives (single-objective vs. multi-objective), the nature of decision variables (deterministic vs. stochastic) and mathematical structures (linear vs. non-linear, discrete vs. continuous).

Single-objective models optimize one specific criterion, such as minimizing costs or maximizing efficiency, making them simpler to formulate and solve. These models are suitable for problems with a clear, dominant objective, such as minimizing transportation costs in a supply chain by determining optimal facility locations and vehicle routes (Alothaimeen and Ardit, 2020). In contrast, multi-objective models consider multiple criteria simultaneously, balancing economic, environmental and social goals. These models generate a Pareto frontier of optimal solutions, crucial for supply chains aiming to balance cost reduction with sustainability and service improvements (Hao et al., 2022). However, multi-objective optimization is complex and computationally

intensive, requiring deep domain knowledge and often lacking transparency, which can limit trust and acceptance (Susinchain, 2022).

Models can also be categorized based on decision variable nature: deterministic models assume certainty in parameters, suitable for stable environments and stochastic models that incorporate uncertainty and variability in parameters, making them suitable for dynamic and unpredictable environments (Alothaimen and Arditi, 2020); discrete models handle specific value decisions, essential for facility location and vehicle routing problems (Guo et al., 2023; Ghosal et al., 2023) and continuous models allow variable values within ranges, ideal for optimizing transportation networks (Govindan et al., 2015). Linear models, easier to solve and interpret, are widely used in resource allocation and production planning (Irawan et al., 2022; Melo et al., 2009), while non-linear models address real-world complexities like economies of scale and complex cost structures (Zhang et al., 2023; Estrada-Garcia et al., 2023).

The choice between single-objective and multi-objective models, deterministic and stochastic approaches and linear versus non-linear or discrete versus continuous models depends on the specific characteristics and requirements of the supply chain problem at hand. By carefully selecting and tailoring these models, supply chain practitioners can develop robust and efficient solutions that address the complexities and trade-offs inherent in modern supply chain networks (Ge et al., 2022).

A general facility location problem involves a set of spatially distributed customers and a set of facilities to serve customer demands. Melo et al. (2009) considers that this problem often requires a trade-off between the fixed costs of establishing facilities and the variable transportation costs associated with serving customers from these facilities. This problem can also be extrapolated to the relationship between suppliers and potential factories, as shown in Figure 2.3.

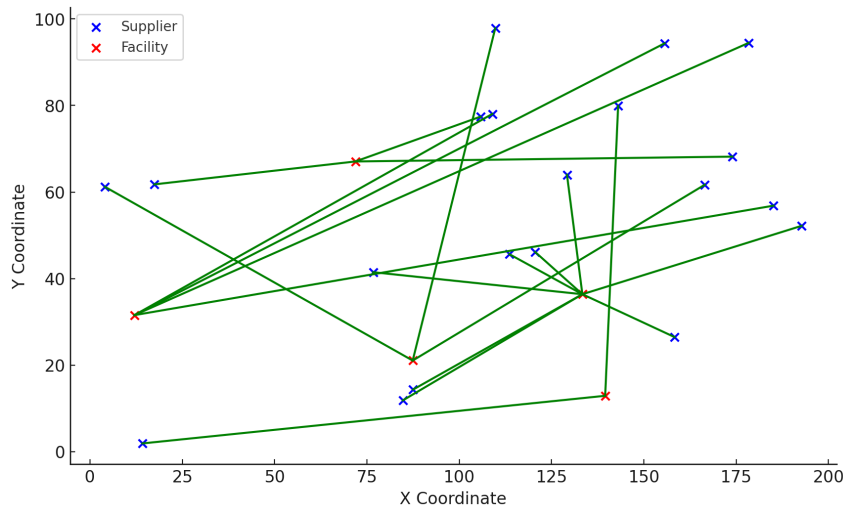


Figure 2.3: Facility location problem representation

Facility location problems can be static or dynamic. Static location problems assume that the parameters such as demand and transportation costs do not change over time. This simpli-

fication allows for more straightforward models but may not be realistic for long-term planning (Alothaimeen and Ardit, 2020). In contrast, dynamic location problems account for changes over time, such as variations in demand, facility capacities and transportation costs. These models are more complex but provide more accurate and adaptable solutions for evolving supply chain networks (Estrada-Garcia et al., 2023).

The center of gravity method is a simple yet effective heuristic used in facility location problems to find an approximate location for a single facility that minimizes the transportation costs. This method calculates the weighted average of the coordinates of demand points, where weights are typically the demands at these points (Iqbal et al., 2023). While this method provides a quick and easy solution, it is often used as an initial estimate in more sophisticated optimization models (Melo et al., 2009).

When a simultaneous choice of nodes (facilities) and arcs (transportation routes) is required, the problem is usually referred to as a network design problem. These problems are more complex because they involve decisions on both facility locations and the transportation network that connects them (G. et al., 2019). The development of a Supply Chain Network Design (SCND) model must balance realism, scope, complexity and solvability. Ensuring that the model is both realistic and solvable often requires simplifying assumptions, which can affect the accuracy of the results (Melo et al., 2009).

One of the main challenges in facility location problems is determining the optimal balance between the costs of establishing facilities and the costs associated with transportation. This is the traditional facility location problem that often involves minimizing the total cost, which includes fixed costs of setting up facilities and variable transportation costs (Guo et al., 2023). Another challenge is dealing with the uncertainties in demand and supply, which can significantly affect the optimal locations of facilities.

Advanced optimization techniques such as Mixed-Integer Linear Programming (MILP) and metaheuristic algorithms like genetic algorithms and simulated annealing are often used to solve complex facility location and network design problems. These techniques can handle large-scale problems and provide near-optimal solutions within reasonable computational times (Farahani et al., 2021). Additionally, incorporating robust optimization methods can help in managing uncertainties by providing solutions that are less sensitive to variations in input data (Ben-Tal et al., 2022).

The insect industry, which involves the production of insects for various purposes such as animal feed, human consumption and bio-waste management, presents unique challenges and opportunities for facility location and network design optimization. The strategic placement of insect production facilities can significantly impact operational efficiency, cost-effectiveness and environmental sustainability. Insect production facilities need to be strategically located to minimize transportation costs for both raw materials (such as organic waste used to feed insects) and the distribution of final products (insect protein, oil, and frass). The location should also consider proximity to markets, regulatory environments and local climatic conditions, which can affect insect growth rates and facility operations (Halloran et al., 2018).

Determining the optimal size and capacity of insect production facilities is crucial. It involves assessing the demand for insect-based products, the availability of feedstock and potential scale economies. Dynamic facility location models can be particularly useful here, allowing for adjustments based on changing market demands and feedstock availability (Oonincx et al., 2022). Furthermore, insect production can be integrated with existing agricultural systems, such as using agricultural by-products as feedstock for insects or locating insect facilities near livestock farms to provide high-protein feed. This integration can create synergies, reduce waste and enhance the sustainability of both the insect production and agricultural sectors (van Huis, 2020).

Optimizing the location and network design of insect production facilities can reduce the carbon footprint associated with transportation and enhance the economic viability of insect-based products. This optimization requires a comprehensive analysis of environmental impacts and cost-benefit assessments to ensure sustainable and profitable operations (Parodi et al., 2018). In conclusion, facility location problems and network design optimization are critical components of the insect industry supply chain management. Addressing these problems requires a careful balance between cost considerations and practical constraints, often employing advanced optimization techniques to derive effective and implementable solutions.

### **2.2.2 Location problems in the insect-based supply chain**

In a project guided by Agenda InsectERA, Borba (2023) developed a model to optimize supply chain networks for insect farming, utilizing a linear cost-minimizing approach to determine optimal locations for insect-rearing plants. The model considers factors such as transportation costs from suppliers to consumers, processing costs and fixed costs such as land, labor and capital. Its main objective is to minimize total costs while ensuring customer demand is met and adhering to the capacity constraints of plants and suppliers. Using MILP, the model provides precise decision-making in complex logistical scenarios, making it adaptable to various insect-based supply chains, products, feed materials, production processes and operational scales. Additionally, the model accounts for the seasonality of substrate availability and different vehicles for transporting substrates, products and frass. The objective function minimizes acquisition costs of substrates, transportation costs, preprocessing costs and fixed operational costs, ensuring a comprehensive optimization of insect farming supply chains.

Another relevant model was developed by Suckling et al. (2021) that created an optimization-based Decision Support Tool (DST) to inform bioconversion businesses about the optimal locations to source surplus foodstuffs, locate processing facilities and determine the most viable business model. The focus is on using BSFL for bioconversion of surplus foodstuffs, specifically spent brewer's grains, into animal feed. The study evaluates three business models: one using live BSFL to feed local poultry and two based on dried BSFL meal used in aquaculture feeds. The live BSFL business model is found to be the most viable, offering the best margins and greatest resilience to model perturbations. The optimization model developed in this study includes several key components:

- Income from processing surplus foodstuff
- Costs of transport and surplus processing
- Costs of post-processing, either decentralized or centralized

The DST uses these components to help businesses understand the best locations for their Bio-conversion Unit (BCU)s and the most suitable business models to adopt. This approach highlights the practicality of insect bioconversion within current supply chains and emphasizes the importance of localizing BCUs to minimize transportation costs and maintain food hygiene standards.

Mouhrim et al. (2022) developed a multi-objective optimization framework for sustainable insect production chains, balancing economic, environmental and social objectives using the Non-dominated Sorting Genetic Algorithm II (NSGA-II) to handle conflicting objectives and generate a Pareto front of optimal solutions. The economic objective aims to maximize operating profit by optimizing insect biomass production, feed conversion efficiency and reducing labor costs. The environmental objective targets minimizing the ecological footprint, particularly greenhouse gas emissions from frass disposal, while the social objective includes factors such as Fair Wage Potential (FWP) and Labor Safety (LS) to improve social sustainability. The approach involves developing models describing the conflicting objective functions and optimizing them using NSGA-II. Results indicate that small-scale facilities can achieve near-optimal social sustainability, whereas larger-scale facilities face challenges in balancing economic and environmental objectives. The observed discontinuity in the Pareto front suggests industry viability at small and very large scales, highlighting the need for further research to refine the model and incorporate more comprehensive environmental impact assessments.

The model developed in this dissertation is based on the three models previously described. This work is a continuation of that conducted by Borba (2023), incorporating many of the aspects considered in his model. The main differences between the two models lies in the objective functions, number of insects considered and percentages of types of raw materials. While Borba's model focuses solely on the economic aspect of the problem (constructed in a manner very similar to that used for this model), the present model also includes a sustainable component, making it multi-objective and resulting in completely different outcomes and interpretations. Furthermore, the model described in this paper delves deeper into the possibility of constructing factories that produce different types of insects, as well as the variation of certain parameters across different districts of Portugal. Another critical factor added to this model was the minimum percentage of types of raw materials required for the production of substrates to feed the insects, ensuring the normal operation of the facilities.

Regarding the other models previously presented, Suckling's model serves as a solid foundation for the economic aspect of the problem and provides useful references for how results can be analyzed. Mouhrim's model, although presenting a simplified analysis of results, incorporates different objective functions for the model, covering economic, environmental and social dimensions. However, the present model considers different economic and environmental goals and uses

a different approach to handle the conflicting objectives. Similar to Borba's model, the model presented in this dissertation represents an evolution in relation to these two articles, as it is designed for a pre-established industry and adapted to different periods of the year, types of substrates and insects.

## Chapter 3

# Problem description and modeling

In this section, the problem will be addressed with more detail and rigor. In addition to providing context to its objectives, the programming model used to optimize the construction of new facilities for insect production will be introduced.

For the problem formulation, a set of inputs necessary for solving the model were defined. Additionally, this section also presents the objective functions and constraints used to obtain optimal solutions and analyze different scenarios.

### 3.1 Inputs definition and description

The developed project primarily focuses on optimizing the supply chain of the insect industry in Portugal, with a specific emphasis on the connection between suppliers and production facilities of the respective insects. Therefore, the project is based on creating an optimization model that identifies the best locations for logistic hotspots.

Only the facility is considered the link between suppliers and production (single-echelon). The main focus is on the suppliers and the possible facilities since this is the critical problem at the moment, as consumers are not yet considered an important factor in the insect industry supply chain.

In this study three insect hypotheses will be considered: black soldier fly (*Hermetia illucens*), mealworm (*Tenebrio molitor*) and domestic cricket (*Acheta domesticus*). Thus, the model incorporates the possibility that a facility can be constructed to producing one of these three insects. Figure 3.1 shows the inputs from the possible facilities locations incorporated into the model. There are parameters identical for the different insects, but others are critical in the final decision-making, so the model will include a set B of possible facilities for the production of black soldier fly, a set M for mealworm production, and a set C for domestic cricket production. Since the possible facility locations are the same for the different insects, the fixed costs ( $CF_b$ ,  $CF_m$ , and  $CF_c$ ) will be the same.

For the construction of the facility, its inventory capacity ( $IC_b$ ,  $IC_m$ , and  $IC_c$ ) and processing capacity ( $PC_b$ ,  $PC_m$ , and  $PC_c$ ) must be considered. Among the parameters that differ according

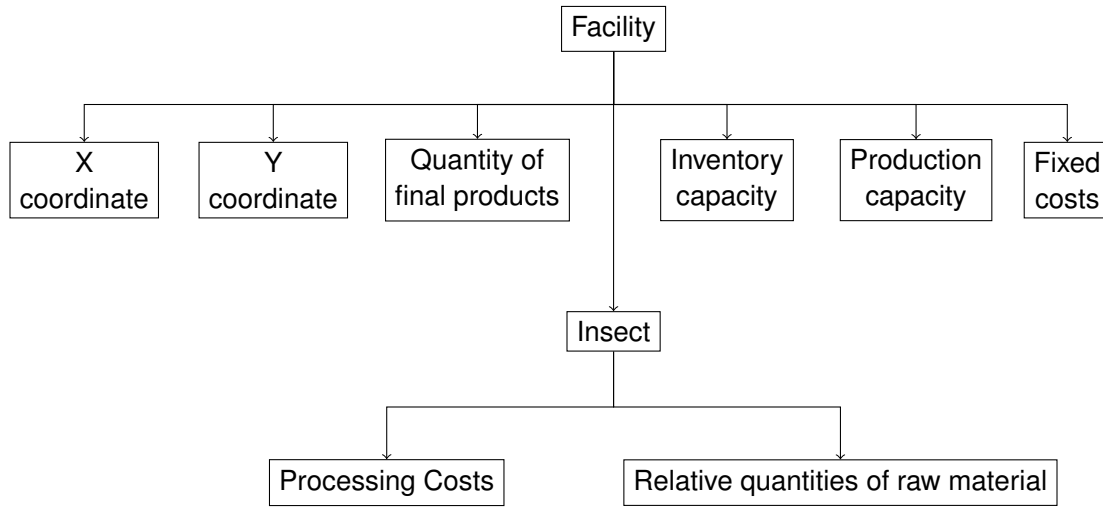


Figure 3.1: Inputs from facilities

to the insects are the processing costs ( $CP_b$ ,  $CP_m$ , and  $CP_c$ ), as they vary according to the number and complexity of processing stages and the required percentages of each type of raw material for their production ( $W_{bp}$ ,  $W_{mp}$ , and  $W_{cp}$ ). It should be noted that these percentages differ for the various insects, as they require different substrate compositions. Finally, for each facility, it is also important to understand the required final production percentage compared to the production capacity ( $PR_b$ ,  $PR_m$ , and  $PR_c$ ).

The model also includes a set of possible suppliers, included in set I, associated with the raw material they produce and the quantity available in a given period, with this availability varying throughout the different periods due to external factors. Additionally, the associated raw material has a cost, referred to in the model as the acquisition cost ( $CA_{ilt}$ ). The Figure 3.2 reflects the input parameters from the suppliers.

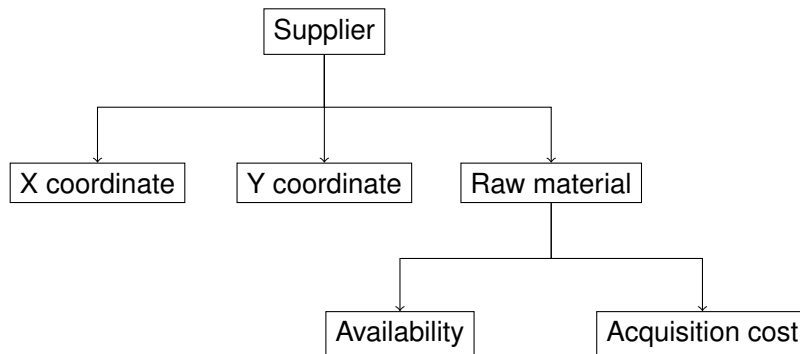


Figure 3.2: Inputs from suppliers

The different raw materials, given by L, belong to a certain type, in a set of P types of raw materials (vegetal, fruit and nut). It should be noted that a raw material can only be considered of one given type. Furthermore, each raw material has a CR associated with each of the three insects. The CR is calculated by Equation (3.1) and expresses the quantity of raw material consumed by

the insect during its development period.

$$CR = \frac{\text{mass of insects}}{\text{mass of substrate}} \quad (3.1)$$

To create a realistic model, it is necessary to include different periods of the year (in set T) when supply may change due to various factors. One-month periods were considered for modeling and obtaining the best solution to the problem. Incorporating all these factors into the final model will ensure that the location of the facility is as appropriate as possible.

With all of this information we can define the model inputs as follows:

#### Sets

|   |                |                                         |
|---|----------------|-----------------------------------------|
| I | = { 1,...,n }, | set of suppliers                        |
| B | = { 1,...,n }, | set of facilities for black soldier fly |
| M | = { 1,...,n }, | set of facilities for mealworm          |
| C | = { 1,...,n }, | set of facilities for domestic cricket  |
| L | = { 1,...,n }, | set of raw material                     |
| T | = { 1,...,n }, | set of periods                          |
| P | = { 1,...,n }, | set of types of raw materials           |

#### Parameters

|        |           |                                                              |
|--------|-----------|--------------------------------------------------------------|
| NB     |           | minimum number of facilities to locate for black soldier fly |
| NM     |           | minimum number of facilities to locate for mealworm          |
| NC     |           | minimum number of facilities to locate for domestic cricket  |
| $IC_b$ | [t/month] | inventory capacity of facility b                             |
| $IC_m$ | [t/month] | inventory capacity of facility m                             |
| $IC_c$ | [t/month] | inventory capacity of facility c                             |
| $PC_b$ | [t/month] | production capacity of facility b                            |
| $PC_m$ | [t/month] | production capacity of facility m                            |
| $PC_c$ | [t/month] | production capacity of facility c                            |

|                 |           |                                                                                   |
|-----------------|-----------|-----------------------------------------------------------------------------------|
| $M_{sup_{ilt}}$ | [t/month] | availability of raw material $l$ of supplier $i$ in period $t$                    |
| $VC$            | [t]       | maximum capacity of vehicle used for raw materials transportation                 |
| $d_{ib}$        | [Km]      | distance between supplier $i$ and facility $b$                                    |
| $d_{im}$        | [Km]      | distance between supplier $i$ and facility $m$                                    |
| $d_{ic}$        | [Km]      | distance between supplier $i$ and facility $c$                                    |
| $CV$            | [€/Km]    | cost of operating vehicle                                                         |
| $CF_b$          | [€]       | fixed cost of operating facility $b$                                              |
| $CF_m$          | [€]       | fixed cost of operating facility $m$                                              |
| $CF_c$          | [€]       | fixed cost of operating facility $c$                                              |
| $CA_{ilt}$      | [€/t]     | acquisition cost of raw material $l$ of supplier $i$ in period $t$                |
| $CP_b$          | [€/t]     | processing costs in facility $b$                                                  |
| $CP_m$          | [€/t]     | processing costs in facility $m$                                                  |
| $CP_c$          | [€/t]     | processing costs in facility $c$                                                  |
| $Z_{lp}$        |           | relation matrix between the raw materials and their type                          |
| $W_{bp}$        |           | minimum relative quantity of raw material type to be transported to facility $b$  |
| $W_{mp}$        |           | minimum relative quantity of raw material type to be transported to facility $m$  |
| $W_{cp}$        |           | minimum relative quantity of raw material type to be transported to facility $c$  |
| $PR_b$          |           | minimum relative quantity of final products produced in facility $b$              |
| $PR_m$          |           | minimum relative quantity of final products produced in facility $m$              |
| $PR_c$          |           | minimum relative quantity of final products produced in facility                  |
| $CR$            |           | matrix with the conversion ratios of raw material $l$ for the different insects   |
| $E_b$           | [t/Km]    | $CO_2$ emissions associated with transportation for Black Soldier Fly facilities  |
| $E_m$           | [t/Km]    | $CO_2$ emissions associated with transportation for Mealworm facilities           |
| $E_c$           | [t/Km]    | $CO_2$ emissions associated with transportation for Domesticus Cricket facilities |

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Regarding the decision variables to be optimized to achieve the lowest cost and emissions values, the model incorporates the following ones:

$$Y_b = \begin{cases} 0, & \text{facility b is not constructed} \\ 1, & \text{facility b is constructed} \end{cases}$$

$$Y_m = \begin{cases} 0, & \text{facility m is not constructed} \\ 1, & \text{facility m is constructed} \end{cases}$$

$$Y_c = \begin{cases} 0, & \text{facility c is not constructed} \\ 1, & \text{facility c is constructed} \end{cases}$$

$X_{iblt} \in \mathbb{R}_{\geq 0} [t]$ , quantity of raw material  $l$  transported in period  $t$  from supplier  $i$  to facility  $b$

$X_{imlt} \in \mathbb{R}_{\geq 0} [t]$ , quantity of raw material  $l$  transported in period  $t$  from supplier  $i$  to facility  $m$

$X_{iclt} \in \mathbb{R}_{\geq 0} [t]$ , quantity of raw material  $l$  transported in period  $t$  from supplier  $i$  to facility  $c$

### 3.2 Objective functions

Given the constant sustainable development, the model must include not only economic aspects but also environmental ones. The economic aspects include costs related to the acquisition and transportation of raw materials, installation and maintenance of new facilities (fixed costs) and processing costs. Acquisition costs vary according to the type of raw material supplied and the time of year due to fluctuations in availability, while transportation costs are directly linked to the distance between the supplier and the facility. Fixed costs cover the installation and maintenance of the facility and processing costs encompass all logistics related to the breeding and processing of insects within the facility. Environmental aspects will include  $CO_2$  emissions related to the transportation of raw materials.

With all the model inputs, it is possible to construct the objective functions that will reflect the optimal value of costs and emissions, according to the priorities given to each. The cost objective function is given by the following expression:

$$OF_{Costs} = \sum_{i \in I} \sum_{l \in L} \sum_{b \in B} \sum_{t \in T} X_{iblt} \cdot CA_{ilt} \quad (3.2)$$

$$+ \sum_{i \in I} \sum_{l \in L} \sum_{b \in B} \sum_{t \in T} \left( X_{iblt} \cdot \frac{CV}{VC} \cdot d_{ib} \right) \quad (3.3)$$

$$+ \sum_{i \in I} \sum_{l \in L} \sum_{b \in B} \sum_{t \in T} X_{iblt} \cdot CP_b \quad (3.4)$$

$$+ \sum_{b \in B} Y_b \cdot CF_b \quad (3.5)$$

$$+ \sum_{i \in I} \sum_{l \in L} \sum_{m \in M} \sum_{t \in T} X_{imlt} \cdot CA_{ilt} \quad (3.6)$$

$$+ \sum_{i \in I} \sum_{l \in L} \sum_{m \in M} \sum_{t \in T} \left( X_{imlt} \cdot \frac{CV}{VC} \cdot d_{im} \right) \quad (3.7)$$

$$+ \sum_{i \in I} \sum_{l \in L} \sum_{m \in M} \sum_{t \in T} X_{imlt} \cdot CP_m \quad (3.8)$$

$$+ \sum_{m \in M} Y_m \cdot CF_m \quad (3.9)$$

$$+ \sum_{i \in I} \sum_{l \in L} \sum_{c \in C} \sum_{t \in T} X_{iclt} \cdot CA_{ilt} \quad (3.10)$$

$$+ \sum_{i \in I} \sum_{l \in L} \sum_{c \in C} \sum_{t \in T} \left( X_{iclt} \cdot \frac{CV}{VC} \cdot d_{ic} \right) \quad (3.11)$$

$$+ \sum_{i \in I} \sum_{l \in L} \sum_{c \in C} \sum_{t \in T} X_{iclt} \cdot CP_c \quad (3.12)$$

$$+ \sum_{c \in C} Y_c \cdot CF_c \quad (3.13)$$

Expressions (3.2), (3.6) and (3.10) represents the acquisition costs given by multiplying the transported quantity by the associated acquisition cost.

Expressions (3.3), (3.7) and (3.11) represents the transportation costs given by multiplying the transported quantity by the distance between the supplier and the facility and by dividing the vehicle operating costs by the vehicle's maximum capacity.

Expressions (3.4), (3.8) and (3.12) represents the processing costs given by multiplying the transported quantity by the insect processing cost.

Finally, expressions (3.5), (3.9) and (3.13) represents the fixed costs associated with the construction and maintenance of the facilities.

As for the environmental objective function, it can be expressed as follows:

$$OF_{Emissions} = \sum_{i \in I} \sum_{l \in L} \sum_{b \in B} \left( \sum_{t \in T} \frac{X_{iblt}}{VC} \cdot d_{ib} \cdot E_b \right) \quad (3.14)$$

$$+ \sum_{i \in I} \sum_{l \in L} \sum_{m \in M} \left( \sum_{t \in T} \frac{X_{imlt}}{VC} \cdot d_{im} \cdot E_m \right) \quad (3.15)$$

$$+ \sum_{i \in I} \sum_{l \in L} \sum_{c \in C} \left( \sum_{t \in T} \frac{X_{iclt}}{VC} \cdot d_{ic} \cdot E_c \right) \quad (3.16)$$

Expressions (3.14), (3.15) and (3.16) represent  $CO_2$  emissions given by multiplying the emissions per kilometer by the kilometers traveled. The kilometers traveled are given by multiplying the transported quantity by the distance between the supplier and the facility and by dividing by the vehicle's maximum capacity.

For calculating  $CO_2$  emissions from transport vehicles, the model created by the European Environment Agency (EEA) (Ntziachristos and Samaras, 2018) was used, where hot emissions  $E(v)$  are calculated based on average speed  $v$  using Equation (3.17).

$$E(v) = \left( \frac{a_1 \cdot v^2 + a_2 \cdot v + a_3 + \frac{a_4}{v}}{a_5 \cdot v^2 + a_6 \cdot v + a_7} \right) \cdot \beta \quad (3.17)$$

where  $a_1$ – $a_7$  are coefficients that differ by fuel, vehicle class, and engine technology, and  $\beta$  is a correction factor applied, if necessary, to account for different types of roads.

The districts differ in terms of speed averages, as the average speeds vary depending on potential locations. By applying the emissions calculation model for different speeds, a relationship between  $CO_2$  emissions and speeds is obtained, as shown in Figure 3.3.

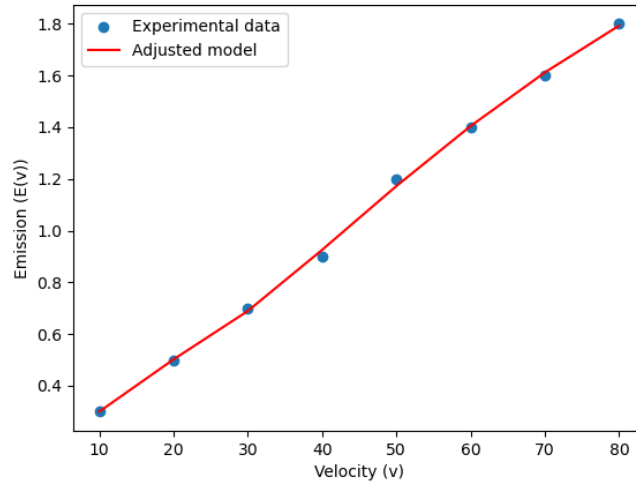


Figure 3.3: Emissions of  $CO_2$  for different velocities

By applying the model, it is possible to obtain the different values of  $E_b$ ,  $E_m$ , and  $E_c$  for the various considered locations. For this, the speeds presented in Table A.1 of Appendix B were used to calculate  $CO_2$  emissions. The values of  $E_b$ ,  $E_m$ , and  $E_c$  are the same for the same values of  $b$ ,  $m$ , and  $c$ , respectively, but they are used at different times for the various insects.

### 3.3 Constraints

The model comprises a set of constraints to make it more reliable.

$$\sum_{b \in B} X_{iblt} + \sum_{m \in M} X_{imlt} + \sum_{c \in C} X_{iclt} \leq Msup_{ilt}, \quad \forall i \in I, l \in L, t \in T \quad (3.18)$$

$$\sum_{i \in I} \sum_{l \in L} X_{iblt} \leq IC_b \cdot Y_b, \quad \forall b \in B, t \in T \quad (3.19)$$

$$\sum_{i \in I} \sum_{l \in L} X_{imlt} \leq IC_m \cdot Y_m, \quad \forall m \in M, t \in T \quad (3.20)$$

$$\sum_{i \in I} \sum_{l \in L} X_{iclt} \leq IC_c \cdot Y_c, \quad \forall c \in C, t \in T \quad (3.21)$$

$$\sum_{i \in I} \sum_{l \in L} X_{iblt} \cdot CR \geq PR_b \cdot PC_b \cdot Y_b, \quad \forall b \in B, t \in T \quad (3.22)$$

$$\sum_{i \in I} \sum_{l \in L} X_{imlt} \cdot CR \geq PR_m \cdot PC_m \cdot Y_m, \quad \forall m \in M, t \in T \quad (3.23)$$

$$\sum_{i \in I} \sum_{l \in L} X_{iclt} \cdot CR \geq PR_c \cdot PC_c \cdot Y_c, \quad \forall c \in C, t \in T \quad (3.24)$$

$$\sum_{i \in I} \sum_{l \in L} X_{iblt} \cdot Z_{lp} \geq W_{bp} \cdot \sum_{i \in I} \sum_{l \in L} X_{iblt}, \quad \forall p \in P, b \in B, t \in T \quad (3.25)$$

$$\sum_{i \in I} \sum_{l \in L} X_{imlt} \cdot Z_{lp} \geq W_{mp} \cdot \sum_{i \in I} \sum_{l \in L} X_{imlt}, \quad \forall p \in P, m \in M, t \in T \quad (3.26)$$

$$\sum_{i \in I} \sum_{l \in L} X_{iclt} \cdot Z_{lp} \geq W_{cp} \cdot \sum_{i \in I} \sum_{l \in L} X_{iclt}, \quad \forall p \in P, c \in C, t \in T \quad (3.27)$$

$$\sum_{b \in B} Y_b \geq NF_b, \quad (3.28)$$

$$\sum_{m \in M} Y_m \geq NF_m, \quad (3.29)$$

$$\sum_{c \in C} Y_c \geq NF_c, \quad (3.30)$$

$$X_{iblt}, X_{imlt}, X_{iclt} \geq 0, \quad (3.31)$$

$$Y_b, Y_m, Y_c \in \{0, 1\} \quad (3.32)$$

Expression (3.18) establishes the maximum availability of raw materials from suppliers. On the other hand, it is also important to define constraints regarding the maximum capacity of the different facilities, as can be analyzed in expressions (3.19), (3.20) and (3.21) for the black soldier fly, mealworm and domesticus cricket facilities, respectively..

Expression (3.22), (3.23) and (3.24) reflects the satisfaction of minimum production of final products for the different facilities. In terms of quantity transported of each type of raw material, expressions (3.25), (3.26) and (3.27) reflects these satisfactions for the different facilities.

Expressions (3.28), (3.29) and (3.30) establishes the minimum number of facilities to be located for the different types of insects.

Finally, expression (3.31) ensures that all continuous variables are non-negative and expression (3.32) ensures that the variables  $Y_b$ ,  $Y_m$ , and  $Y_c$  only take the values 0 or 1.

## Chapter 4

# Methodology

This optimization problem was approached as a MILP problem, which entails finding the optimal solution through a linear objective function, constrained by a set of linear restrictions, with the decision variables being integers and continuous. MILP is a generalization of Linear Programming (LP), which handles continuous variables, and Integer Programming (IP), which deals with variables that must assume integer values (Bixby, 2012).

Accordingly, the objective functions are linear, with constant coefficients. In cases of non-linear relationships, certain functions were applied to linearize the objective functions. In the case of the model, it is deterministic, incorporating no uncertainties. For existing uncertainties, subsequent sensitivity analyses were employed to enhance the model's coherence and reliability.

Therefore, given that these location points are predefined, we are addressing a discrete location problem. The model will incorporate the possibility of locating plants throughout Portugal, dividing the possible locations according to districts. With this information, it is possible to analyze the best region to locate the facilities. The locations of the suppliers and the possible locations of the facilities are the main inputs for solving our problem, as shown in Figure 4.1.

Regarding transportation, the objective is to minimize the associated costs as much as possible. To optimize the facility location, the p-median method will be utilized to minimize the sum of all distances between suppliers and the facility. To determine these distances between suppliers and potential facilities, the Euclidean distance was used. The Euclidean distance measures the "straight-line" distance between two points in Euclidean space, representing the shortest path between two points, derived from the Pythagorean theorem. Equation 4.1 represents the formula for calculating the respective distances used in the problem's optimization.

$$d(A,B) = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \quad (4.1)$$

To develop and test the model, the Gurobi solver in Python was used. Gurobi is a state-of-the-art solver for mathematical programming, renowned for its efficiency and widely utilized for solving MILP problems due to its advanced algorithms and optimization techniques (Han et al., 2023).

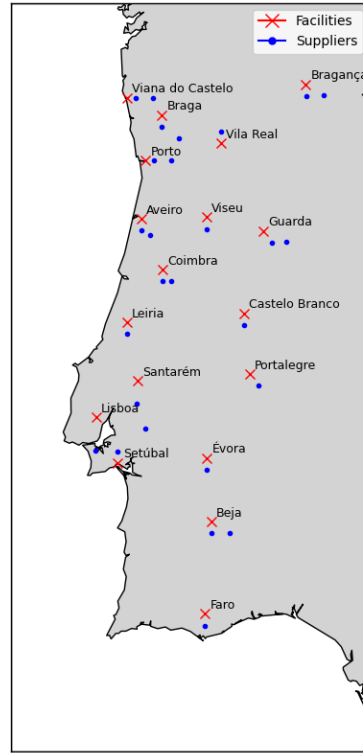


Figure 4.1: Suppliers and facilities locations distribution

Bearing in mind the multi-objective nature of the problem, the various hypotheses for the final solution will be arranged on the Pareto curve. The decision maker will be responsible for the final determination of the facility location, considering the weight they assign to each objective function — whether minimizing costs or enhancing sustainability. To construct the Pareto curve, the Augmented  $\varepsilon$ -Constraint (AUGMENCON) method was employed to generate all possible optimal solutions.

The AUGMENCON method is a sophisticated technique designed to address MultiObjective Mathematical Programming (MOMP) problems. This method refines the traditional  $\varepsilon$ -constraint method by mitigating its limitations, such as the generation of weakly Pareto optimal solutions and redundant iterations (Mavrotas, 2009).

The first step in applying the method involves formulating the problem, which includes defining decision variables, constraints and objective functions. Subsequently, the payoff table is calculated by applying lexicographic optimization to each objective function. This procedure is carried out as follows:

1. Optimize the objective function  $OF_{Costs}$  individually and obtain the best value  $f_{costs}$ .
2. Optimize the objective function  $OF_{Emissions}$  using the additional constraint  $OF_{Costs} = f_{costs}$ .
3. Repeat the previous steps starting by optimizing the objective function  $OF_{Emissions}$  individually.

The payoff table allows us to determine the bounds of each objective function to use as constraints in the  $\varepsilon$ -constraint method. Table 4.1 illustrates the payoff table and the expected outcomes for each optimization.

Table 4.1: Payoff table representation

|                       | $f_{costs}$ | $f_{emissions}$ |
|-----------------------|-------------|-----------------|
| $\min OF_{Costs}$     | min costs   | max emissions   |
| $\min OF_{Emissions}$ | max costs   | min emissions   |

The obtained minimum and maximum values will be used as limits in the constraints imposed on the model. Next, the range of each objective function is divided into 10 equal intervals to create grid points for parameter variation.

To address the problem in an  $\varepsilon$ -constraint form, the  $OF_{Costs}$  function is optimized while imposing the  $OF_{Emissions}$  function as a constraint, incorporating slack or surplus variables to ensure efficiency. The structure of the formulation can be represented as follows:

$$\min \left( OF_{Costs}(x) + \varepsilon \sum_{i=2}^p \frac{s_i}{r_i} \right)$$

subject to

$$OF_{Emissions}(x) + s_i = e_i \quad \forall i = 2, \dots, p$$

$$x \in S, \quad s_i \geq 0$$

where  $s_i$  represents a slack or surplus to ensure that the solutions obtained are Pareto optimal and  $r_i$  is the range of the  $OF_{Emissions}$  objective function.

Finally, solve the above problem for each combination of grid points  $e_i$  to generate Pareto optimal solutions.

All necessary data for optimizing the problem is imported into Python from previously formulated Excel sheets. The only manual input data includes the minimum number of factories to build for each insect, the maximum capacity of each vehicle, the average vehicle consumption, and the average fuel price. With this data, it is possible to optimize the model and determine the set of factories to be constructed based on the constraints imposed on the model.



## Chapter 5

# Results and discussion

In this section, the main results obtained from the optimization of the programming model using the Gurobi tool in Python will be presented and discussed.

Firstly, the results of the base scenario for different costs and  $CO_2$  emissions will be shown. Next, a scenario will be presented where there is only a constraint regarding the minimum number of facilities to be constructed, as well as a scenario where the fixed costs of the various possible locations vary. Finally, the results of a scenario that encompasses the two aforementioned changes will be presented.

An interpretation of the results will also be provided, along with a comparison between the different scenarios to understand the influence of the type of insect and certain variables, such as fixed costs, on the optimal solutions of the problem, presented by a Pareto's curve.

### 5.1 Baseline scenario

All the data used in the study were generated randomly, given the absence of real data currently available to test the model. However, the random data generation was conducted carefully to allow for the analysis of different scenarios and the assessment of certain parameters' influence on the final solution to the problem.

The parameters related to the vehicles were defined based on specific sources to make them more realistic. The maximum capacity of the vehicles for transporting raw materials was set at 5 tons (Trucks, 2024), and the average fuel consumption was fixed at 0,3 L/Km (Solutions, 2024). The diesel price was assumed to be an average current price of around €0,85/L. These data were kept constant for all analyzed scenarios.

The data related to the possible locations of the factories and suppliers were generated in Excel and later incorporated into Python. In Tables A.2, A.3 and A.4 from Appendix A, it is possible to analyze the data generated for the potential factories of black soldier fly, mealworm, and domestic cricket, respectively. The data are similar, with the same values for the coordinates of the possible locations to ensure the best choice of insect to produce at each factory. There are 18 possible locations, each associated with a different district of Portugal. Additionally, the inventory

and processing capacities, as well as the fixed costs of constructing and maintaining the factories, are the same for all locations. The differences lie in the processing costs and the percentage of each type of raw material required for the production of the substrates. The processing costs were assumed to be €400/t, €500/t, and €550/t for black soldier fly, mealworm, and domesticus cricket, respectively (Kooistra, 2020) (Nilapornkul and Aoithongdee, 2019). Minimum percentages of each type of raw material were imposed for the different types of insects in order to satisfy the minimum quantity required for the creation of the substrates. The final production percentage was set at 80% of the production capacity for all factories.

In Table A.5 from Appendix A, the generated data for the suppliers can also be observed. It was assumed that all districts have at least one supplier, who distributes the same raw material throughout the year, providing different quantities in different periods, with the acquisition cost varying according to the raw material supplied.

The model incorporates suppliers of different types of raw materials: three of the vegetable type, four of the fruit type, and three of the nut type. As shown in Table A.6 from Appendix A, these data were incorporated through a matrix relating the different raw materials and their types. Each raw material has an associated CR for each type of insect, varying between 0,5 and 1, as detailed in Table A.7 from Appendix A.

In the baseline scenario, all constraints and objective functions were imposed as described in Chapter 3. Additionally, a minimum of one factory was considered for each type of insect, hence NB, NM, and NC were set to 1. Through the individual optimization of the objective functions, the limits of each were obtained, as can be observed in Table 5.1. By applying the AUGMENCON method, the Pareto curve shown in Figure 5.1 was achieved.

Table 5.1: Payoff table representation for baseline scenario

|                       | $f_{costs}$        | $f_{emissions}$ |
|-----------------------|--------------------|-----------------|
| $\min OF_{Costs}$     | $4,94 \times 10^6$ | 135,85          |
| $\min OF_{Emissions}$ | $4,96 \times 10^6$ | 72,6            |

Over the 10 iterations conducted, there is a significant increase in costs as emissions drop below 100 tons of  $CO_2$ , abruptly rising from  $4,94 \times 10^6$  to  $4,96 \times 10^6$  in just two iterations, corresponding to a 0.35% increase in costs, compared to a 0.06% increase in the first 5 iterations. From the data gathered, it is also concluded that a 0,41% increase in total costs results in an 46,56% reduction in  $CO_2$  emissions.

In terms of the facilities built, these also vary throughout the iterations, as can be seen in Table 5.2. For the black soldier fly, Coimbra was the district selected for the construction of its factory throughout all iterations and for domesticus cricket Porto was also always selected. Throughout all iterations, there was only one change related to the factory selected to produce mealworm, shifting from Lisbon to Portalegre. This change was not very significant, as both districts are located in the

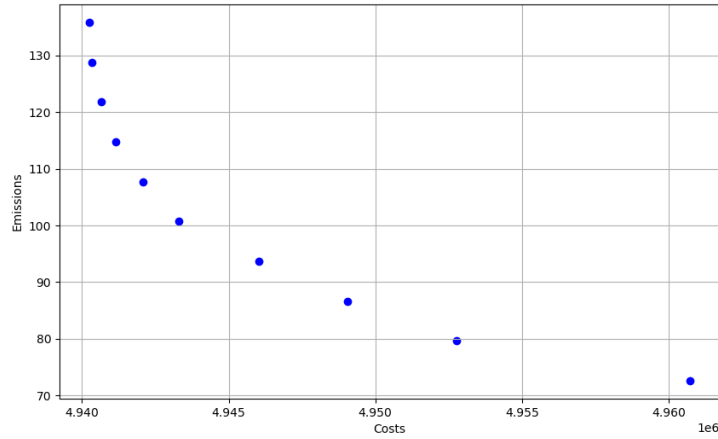


Figure 5.1: Pareto Curve for baseline scenario

central region of mainland Portugal. The differences between the suppliers and facilities selected in the first and last iterations can be observed in Figure 5.2.

Table 5.2: Facilities constructed for the different iterations in the baseline scenario

| Iteration               | Insect type        | Facilities constructed |
|-------------------------|--------------------|------------------------|
| 1, 2 and 3              | Black Soldier Fly  | Coimbra                |
|                         | Mealworm           | Lisboa                 |
|                         | Domesticus Cricket | Porto                  |
| 4, 5, 6, 7, 8, 9 and 10 | Black Soldier Fly  | Coimbra                |
|                         | Mealworm           | <b>Portalegre</b>      |
|                         | Domesticus Cricket | Porto                  |

## 5.2 Scenario with only one restriction related to the minimum number of facilities

Throughout the model's development, various scenarios were considered and tested. Among all the considered hypotheses, the most notable is the modification of constraints related to the number of factories to build for each insect. While the base model imposes an individual minimum number of factories to construct for each insect, differences were also analyzed in the case of imposing only a minimum number of factories to build, regardless of the insect, allowing the solver to choose the order of construction. Thus, the constraints concerning the minimum number of factories to build are reduced to Equation 5.1.

$$\sum_{b \in B} Y_b + \sum_{m \in M} Y_m + \sum_{c \in C} Y_c \geq N \quad (5.1)$$

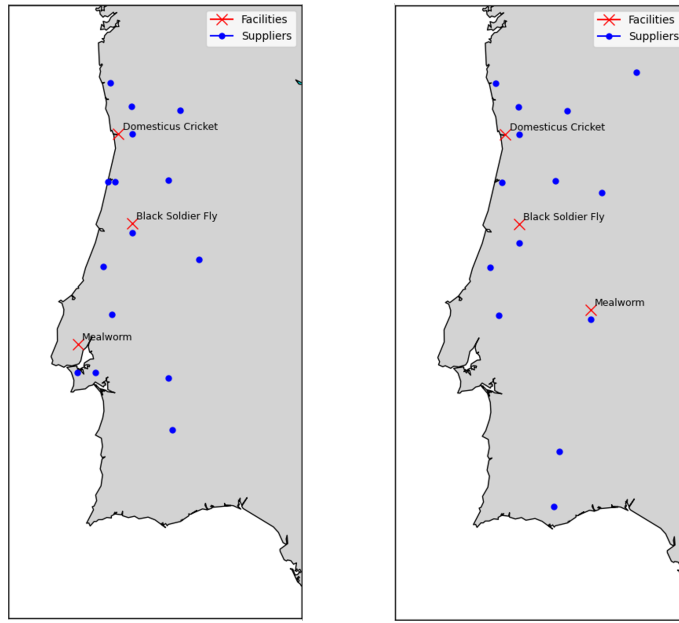


Figure 5.2: Distribution of suppliers and facilities for the first and last iterations in the baseline scenario

In this case, parameter  $N$  was added, replacing parameters  $NB$ ,  $NM$ , and  $NC$ , with a minimum of 3 facilities to be constructed. The results of the maximum and minimum costs, as well as the maximum and minimum emissions for the different model iterations, can be seen in Table 5.3. Regarding cost minimization, there is a 1,13% reduction in the minimum possible cost and a 8,04% reduction when focusing on  $CO_2$  emissions reduction.

Table 5.3: Payoff table representation for scenario with one restriction

|                       | $f_{costs}$        | $f_{emissions}$ |
|-----------------------|--------------------|-----------------|
| $\min OF_{Costs}$     | $4,88 \times 10^6$ | 117,15          |
| $\min OF_{Emissions}$ | $4,91 \times 10^6$ | 66,76           |

A global analysis reveals that a 0,51% increase in costs results in a 43,01% reduction in  $CO_2$  emissions. It is also noticeable in the Pareto curve obtained from resolving this scenario that decreases in emissions are associated with a greater increase in costs as emissions become progressively lower.

Table 5.4 shows that the black soldier fly was the chosen insect for the construction of all three factories in all iterations except for the first two iteration, which considered constructing one factory for mealworm production. The reason for choosing black soldier fly is closely related to its lower processing costs compared to the other insects. The locations of the facilities varied throughout the iterations, with the contrast between the first and last iteration observable in Figure 5.4, respectively.

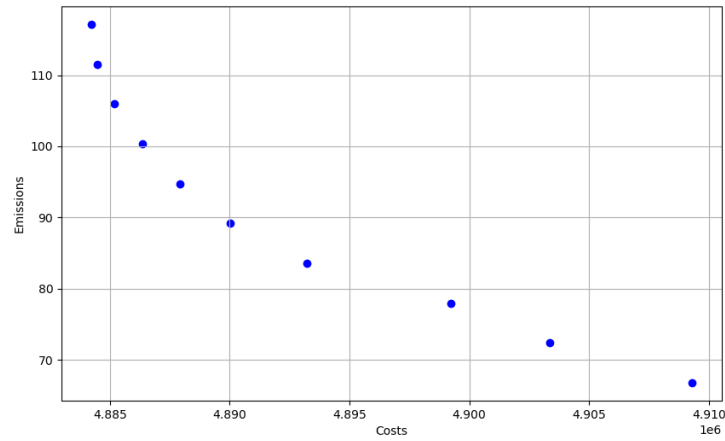


Figure 5.3: Pareto Curve for scenario with one restriction

Table 5.4: Facilities constructed for the different iterations in the scenario with one restriction

| Iteration              | Insect type              | Facilities constructed |
|------------------------|--------------------------|------------------------|
| 1 and 2                | Black Soldier Fly        | Coimbra                |
|                        | Black Soldier Fly        | Porto                  |
|                        | Mealworm                 | Lisboa                 |
| 3, 4, 5, 6, 7, 8 and 9 | Black Soldier Fly        | Coimbra                |
|                        | Black Soldier Fly        | Porto                  |
|                        | <b>Black Soldier Fly</b> | Lisboa                 |
| 10                     | Black Soldier Fly        | <b>Aveiro</b>          |
|                        | Black Soldier Fly        | <b>Braga</b>           |
|                        | Black Soldier Fly        | Lisboa                 |

### 5.3 Scenario with different fixed costs

Besides the distance, fixed costs could also be a variable across the different districts. Therefore, a new scenario was created to understand the influence of these costs on the optimal solution of the problem, since this has a significant impact on the costs, as can be observed in Figure 5.5, obtained by optimizing the base scenario for the minimum possible cost value.

Considering that fixed costs can vary across different districts in Portugal, the base model was tested with variations in fixed costs at different possible facility locations. In Table A.8 from Appendix A, the variation of these costs compared to the base scenario can be observed. The costs were defined in parallel with the population distribution and based on the existing inflation in certain districts.

In the individual optimization of objective functions, the Payoff table shown in Table 5.5 was obtained. Observing the results it is possible to see that a 47,53% increase in total costs results in a 59,12% reduction in  $CO_2$  emissions. The last two iterations corresponds to a significant

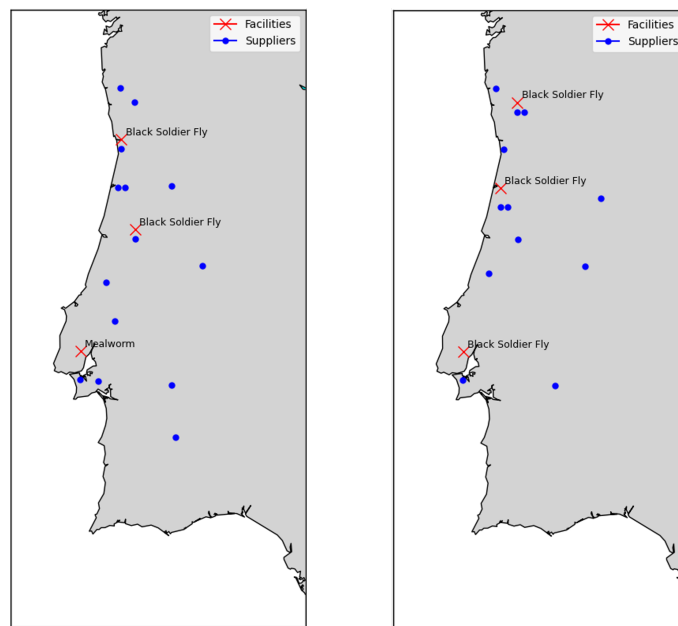


Figure 5.4: Distribution of suppliers and facilities for the first and last iterations in the scenario with one restriction

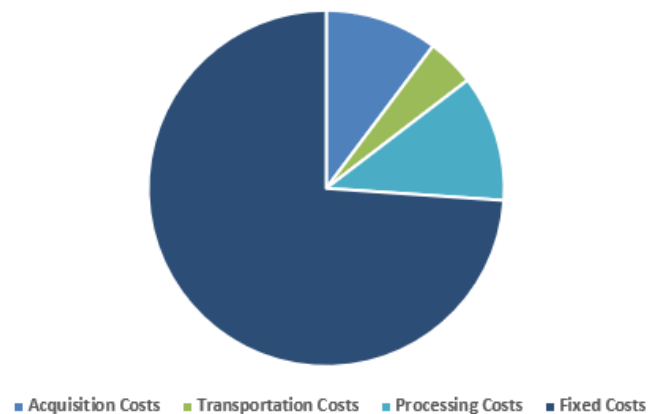


Figure 5.5: Percentage of different costs

increase in costs, as it can be seen in Figure 5.6 with values below 95,93 tons of CO<sub>2</sub> emissions leading to a 46,49% increase in total costs. Overall, the total costs are lower compared to the base scenario, except for the last iteration, which presents a very high cost value, probably due to the data provided to the model. Generally, focusing on cost minimization results in an 18,21% reduction compared to the base scenario, and an equal minimum value for CO<sub>2</sub> emissions when focusing on their minimization.

Table 5.6 shows that the locations of the facilities for the different insects varied over the different iterations, with a significant difference between the first and last iterations, as can be observed in Figure 5.7. It is possible to observe that in the initial iterations where emissions are lower, the facilities constructed correspond to those with higher fixed costs, which is why the total

Table 5.5: Payoff table representation for scenario with different fixed costs

|                       | $f_{costs}$        | $f_{emissions}$ |
|-----------------------|--------------------|-----------------|
| $\min OF_{Costs}$     | $4,04 \times 10^6$ | 177,6           |
| $\min OF_{Emissions}$ | $5,96 \times 10^6$ | 72,6            |

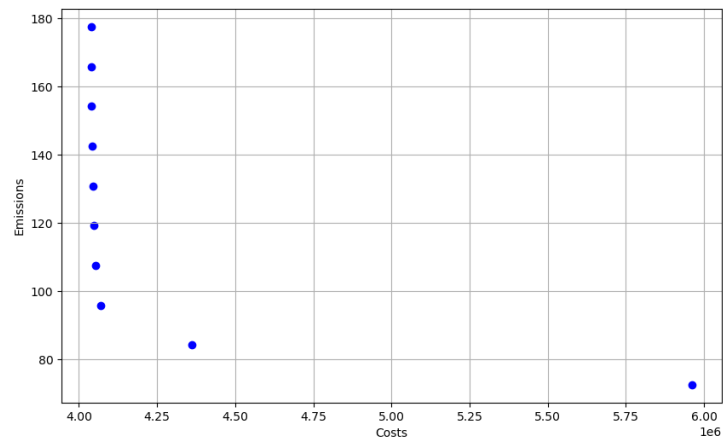


Figure 5.6: Pareto Curve for scenario with different fixed costs

costs are so high. Due to the stringent  $CO_2$  emissions constraint, the model chooses suppliers with shorter distances to the factories, selecting those that are closest to them. As the iterations progress and the  $CO_2$  emissions constraint is relaxed, the selected factories start to show lower fixed costs, leading to a sharp reduction in the total operational costs. Compared to the baseline scenario, it is clear that the choice of locations has already undergone a significant change due to fixed costs, as these have a high impact on the total operational costs.

Table 5.6: Facilities constructed for the different iterations in the scenario with different fixed costs

| Iteration     | Insect type        | Facilities constructed  |
|---------------|--------------------|-------------------------|
| 1             | Black Soldier Fly  | Coimbra                 |
|               | Mealworm           | Lisboa                  |
|               | Domesticus Cricket | Porto                   |
| 2             | Black Soldier Fly  | Coimbra                 |
|               | Mealworm           | <b>Beja</b>             |
|               | Domesticus Cricket | <b>Vila Real</b>        |
| 3             | Black Soldier Fly  | <b>Viana do Castelo</b> |
|               | Mealworm           | <b>Santarém</b>         |
|               | Domesticus Cricket | <b>Beja</b>             |
| 4             | Black Soldier Fly  | Viana do Castelo        |
|               | Mealworm           | Santarém                |
|               | Domesticus Cricket | <b>Vila Real</b>        |
| 5             | Black Soldier Fly  | Viana do Castelo        |
|               | Mealworm           | <b>Castelo Branco</b>   |
|               | Domesticus Cricket | <b>Viseu</b>            |
| 6, 7, 8 and 9 | Black Soldier Fly  | Viana do Castelo        |
|               | Mealworm           | <b>Portalegre</b>       |
|               | Domesticus Cricket | Viseu                   |
| 10            | Black Soldier Fly  | Viana do Castelo        |
|               | Mealworm           | <b>Évora</b>            |
|               | Domesticus Cricket | <b>Vila Real</b>        |

#### 5.4 Scenario with only one restriction related to the minimum number of facilities and different fixed costs

To incorporate all the previous model modifications, a scenario was created with only one restriction regarding the minimum number of factories to be constructed, maintained at  $N=3$ , and the variation of fixed costs with the location of the facilities. The results of the individual optimizations of the objective functions can be observed in Table 5.7, where an even greater reduction in costs, as well as an increase in the limits of  $CO_2$  emissions compared to the baseline scenario, is noted.

Table 5.7: Payoff table representation for scenario with one restriction and different fixed costs

|                       | $f_{costs}$        | $f_{emissions}$ |
|-----------------------|--------------------|-----------------|
| $\min OF_{Costs}$     | $3,98 \times 10^6$ | 149,70          |
| $\min OF_{Emissions}$ | $5,9 \times 10^6$  | 66,76           |

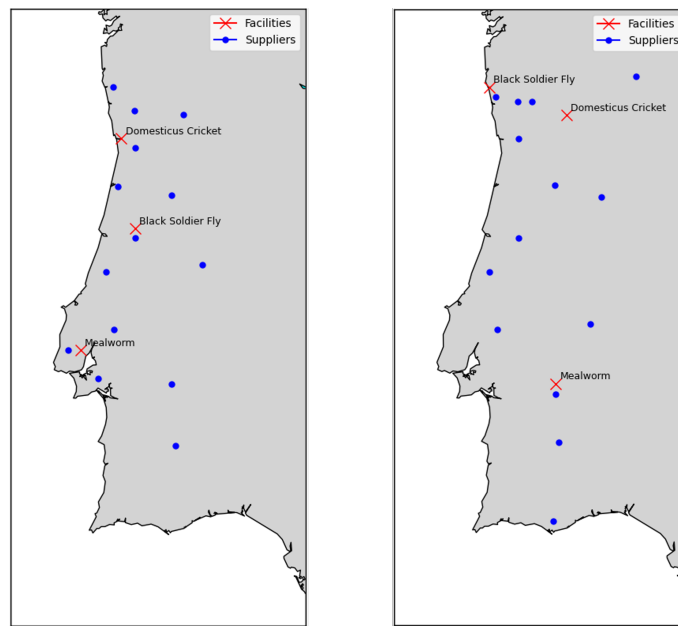


Figure 5.7: Distribution of suppliers and facilities for the first and last iterations in the scenario with different fixed costs

Based on the points used to construct the Pareto curve in Figure 5.8, it can be concluded that focusing solely on cost minimization results in a 19,35% reduction in the minimum cost compared to the baseline scenario and a 8,04% reduction in  $CO_2$  emissions. It is also possible to identify that attempting to reduce  $CO_2$  emissions below 94,41 tons leads to a significant cost increase of 47,51% in the last three transitions, compared to the 0,55% increase in the first six transitions of iterations. It can also be concluded that with these model changes, a 48,32% increase in costs leads to a 55,4% reduction in  $CO_2$  emissions.

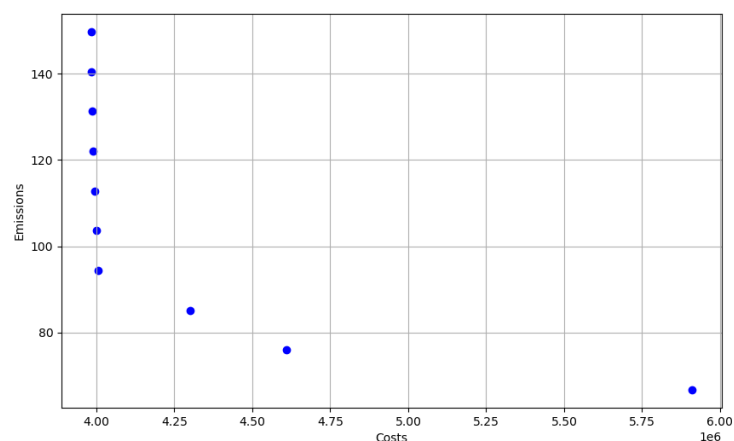


Figure 5.8: Pareto Curve for scenario with one restriction and different fixed costs

In terms of constructed facilities, the model provides an initial optimal solution (where total emissions are lower) with the construction of one mealworm production facility and two black

soldier fly facilities, shifting to the construction of three Black Soldier Fly production facilities, when the costs are the lowest. The reason for this occurrence is due to the previously mentioned fact that the black soldier fly has a lower processing cost compared to the other insects. This evolution can be tracked in Table 5.8, where, as iterations increase, there is an increase in emissions and a consequent decrease in costs. In Figure 5.9, the contrasts between the first and last iterations in the distribution of suppliers and constructed facilities can be observed. As observed in the previous scenario, there is also a transition in the constructed factories concerning fixed costs in this scenario. The greater the relaxation of  $CO_2$  emissions, the easier it is to select factories with lower associated fixed costs.

Table 5.8: Facilities constructed for the different iterations in the scenario with one restriction and different fixed costs

| Iteration         | Insect type              | Facilities constructed  |
|-------------------|--------------------------|-------------------------|
| 1                 | Black Soldier Fly        | Coimbra                 |
|                   | Black Soldier Fly        | Porto                   |
|                   | Mealworm                 | Lisboa                  |
| 2                 | Black Soldier Fly        | Coimbra                 |
|                   | Black Soldier Fly        | <b>Braga</b>            |
|                   | Mealworm                 | <b>Beja</b>             |
| 3                 | Black Soldier Fly        | Coimbra                 |
|                   | Black Soldier Fly        | <b>Viana do Castelo</b> |
|                   | Mealworm                 | <b>Santarém</b>         |
| 4                 | Black Soldier Fly        | <b>Viseu</b>            |
|                   | Black Soldier Fly        | Viana do Castelo        |
|                   | Mealworm                 | Santarém                |
| 5                 | Black Soldier Fly        | Viseu                   |
|                   | Black Soldier Fly        | Viana do Castelo        |
|                   | Mealworm                 | <b>Castelo Branco</b>   |
| 6, 7, 8, 9 and 10 | Black Soldier Fly        | Viseu                   |
|                   | Black Soldier Fly        | Viana do Castelo        |
|                   | <b>Black Soldier Fly</b> | <b>Santarém</b>         |

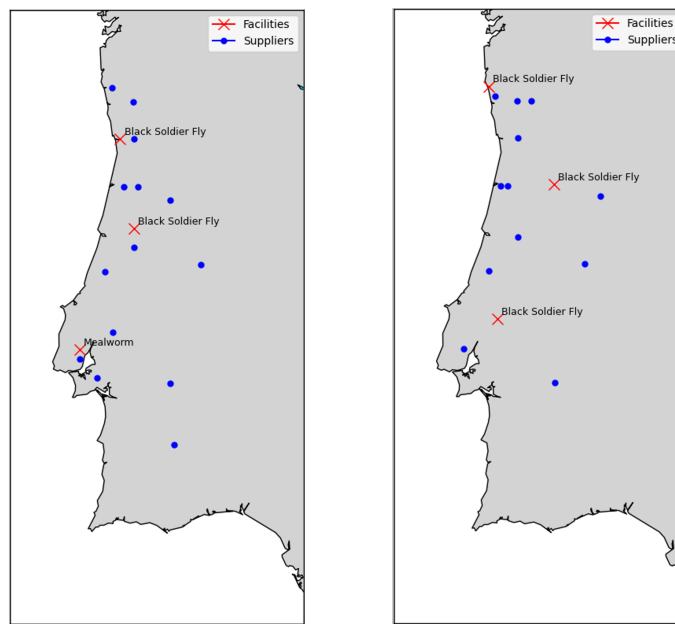


Figure 5.9: Distribution of suppliers and facilities for the first and last iterations in the scenario with one restriction and different fixed costs

## 5.5 Different scenarios comparison

The different tested scenarios present varying results in terms of the optimal allocation of facilities to be constructed, as well as the associated costs and  $CO_2$  emissions. In Tables B.1 and B.2 from Appendix B, a summary of these costs and emissions over all iterations for the different scenarios can be observed.

Tables 5.9 and 5.10 provide a more detailed analysis of the evolution of costs and emissions over the iterations, respectively. In terms of costs, it is possible to identify that their inferior limits decrease in all scenarios, with this decrease being more significant in the scenario where only one restriction on the minimum number of factories to be constructed is implemented, along with a differentiation of fixed costs across different districts of mainland Portugal, with a decrease of 19% of costs. Regarding the upper limits, these increase in scenarios where fixed costs differ, largely due to the limitation of suppliers provided to the model. For emissions, the same trend is similar. The upper limit increases significantly in the last two scenarios, even more so in the scenario with varied fixed costs, showing a 31% increase. The lower limit remains equal to or below that generated in the base scenario.

Table 5.9: Range of costs for the different scenarios

|     | Baseline scenario | 1 restriction | Different fixed Costs | 1 restriction + different fixed costs |
|-----|-------------------|---------------|-----------------------|---------------------------------------|
| Min | 4,94E+06          | 4,88E+06      | 4,04E+06              | 3,984E+06                             |
|     |                   | -1%           | -18%                  | -19%                                  |
| Max | 4,96E+06          | 4,91E+06      | 5,96E+06              | 5,909E+06                             |
|     |                   | -1%           | 20%                   | 19%                                   |

Table 5.10: Range of emissions for the different scenarios

|     | Baseline scenario | 1 restriction | Different fixed Costs | 1 restriction + different fixed costs |
|-----|-------------------|---------------|-----------------------|---------------------------------------|
| Min | 72,60             | 66,76         | 72,60                 | 66,76                                 |
|     |                   | -8%           | 0%                    | -8%                                   |
| Max | 135,85            | 117,15        | 177,60                | 149,70                                |
|     |                   | -14%          | 31%                   | 10%                                   |

These results confirm expectations, as in a multi-objective problem there is always a trade-off between the weighting of different objective functions. Thus, it is always expected that  $CO_2$  emissions will increase when total costs decrease and vice versa.

## Chapter 6

# Conclusion

This dissertation aimed to deepen the optimization of the supply chain in the insect industry in Portugal, considering both economic and environmental aspects. The work focused on solving a facility location problem within the network design of insect production.

Given the innovative nature of this topic, there is still little information and modeling available, both in Portugal and across Europe. Following an extensive literature review, it was concluded that the problem should be addressed as a multi-objective one, integrating a set of suppliers and factories, as well as a set of constraints that confer realism and coherence to the model.

The programming model used includes a list of sets, parameters, decision variables, constraints, and objective functions. The economic objective function covers the total operational costs, including acquisition, transportation, processing and fixed costs of construction and maintenance. The environmental objective function incorporates  $CO_2$  emissions associated with the transportation of raw materials.

To identify the best approach for solving the problem and finding the most suitable solutions, an intensive literature review on the insect industry was conducted to identify parameters that could influence the optimal solutions obtained. The main aspects considered were the type of insect to be produced and its processing costs, the seasonality of raw material availability and acquisition costs, as well as the variation in fixed costs associated with the construction and maintenance of factories across different districts of Portugal. Various iterations were performed to make the model as comprehensive as possible, resulting in a set of optimal solutions for the different scenarios created.

The optimal solutions were obtained through the AUGMENCON method and presented via a Pareto curve, considering different values of  $CO_2$  emissions and total costs associated with one year of operation.

The scenarios created allowed for the analysis of the influence of the type of insect and fixed costs on the optimal solutions of the problem. As observed in the results presented in Chapter 5, processing costs significantly influence the total operational costs. In this context, the Black Soldier Fly is consistently chosen for production when the objective is to minimize costs due to its lower processing costs. On the other hand, fixed costs represent more than 60% of the

total operational costs, making them a critical factor in the analysis. After solving the model incorporating different fixed costs for the various districts of Portugal, it was concluded that it is possible to reduce costs by 18% when aiming for the lowest total cost. This scenario presents a significant discrepancy in costs, with a 48% increase between the upper and lower limits of the different iterations, stemming from the differences in facilities selected to minimize either emissions or costs.

By confirming the influence of the type of insect and fixed costs on the optimal solutions, a final model was developed, combining the previous scenarios and verifying the earlier conclusions. This last scenario showed that the optimal solutions vary significantly in terms of  $CO_2$  emissions and total operational costs, with a 48% increase in total costs when reducing  $CO_2$  emissions by 55%, highlighting the importance of analyzing different optimal solutions and making decisions based on the desired requirements.

The developed thesis addresses the problem described in Chapter 1, providing a contrast between solutions in light of economic and environmental objectives, as well as the variation of some parameters of the optimization model. It is concluded that the project was successfully completed, and all its objectives were achieved with success.

Although the data used as input for the model were created with the utmost care and detail, they are not real data, implying that the solutions obtained may present deviations when real data are introduced. However, the main conclusions will remain valid, with the main limitation being the selected factories for construction, as the possible suppliers and factories will be in different locations and with different associated data.

Other limitations are related to changes over time. The industry is constantly evolving, and since the insect industry is emerging in Portugal, the parameters and objectives may vary over time. Operational costs also undergo frequent changes due to the availability of raw materials, fuel price fluctuations and variations in the real estate market.

For future work, it is suggested to explore the supply chain as a whole, incorporating consumer demand as it becomes relevant with the industry's growth. Incorporating different types of substrates may also be important for greater proximity to reality.

Another improvement suggested is to increase the number of suppliers, allowing the model to find an even more realistic solution. The heuristic used in this model may render the problem intractable if there is a significant increase in the number of suppliers, as it would require a prolonged resolution time for the different scenarios.

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# Contribution to the SDGs

The dissertation titled "Design of the insect-based supply chain in Portugal" presents an innovative and relevant study focused on optimizing the supply chain for the emerging insect industry in Portugal. This project aligns with the United Nations' Sustainable Development Goals (SDGs), particularly concerning the promotion of environmental, social, and economic sustainability.

The research conducted in the thesis highlights the importance of the SDGs and integrates sustainability principles into engineering practices, specifically in industrial engineering and management. The project addresses the growing need for sustainable food solutions, recognizing insect production as an efficient and low-environmental-impact protein source. This focus aligns with SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production).

In terms of environmental impact, the thesis focuses on reducing  $CO_2$  emissions through logistical optimization, a crucial component for mitigating climate change (SDG 13 - Climate Action). Implementing an optimized supply chain reduces the carbon footprint associated with insect transport and processing. Furthermore, integrating circular economy practices in insect production significantly contributes to waste reduction and resource reuse, promoting a more sustainable production model (SDG 12).

On the social aspect, the thesis anticipates creating new jobs in the insect industry in Portugal, contributing to local and regional economic development (SDG 8 - Decent Work and Economic Growth). Insect production as a protein source offers an alternative solution for food security, particularly relevant in resource-scarce regions (SDG 2).

Economically, the thesis demonstrates a significant reduction in operational costs through optimizing the location of logistics centers and factories, increasing the efficiency and economic viability of insect production (SDG 9 - Industry, Innovation, and Infrastructure). Additionally, promoting innovative practices in insect production, such as using advanced technologies for logistical and production optimization, underscores the role of innovation in achieving sustainability goals (SDG 9).

The study not only achieves its objectives but also provides a clear vision of the challenges and solutions for building an efficient and sustainable supply chain for insect production, promoting innovation and the global green transition.



# Appendix A

## Input Data

Table A.1: Velocities of trucks for the different locations

| Location         | Velocity (Km/h) |
|------------------|-----------------|
| Aveiro           | 70              |
| Beja             | 60              |
| Braga            | 65              |
| Bragança         | 55              |
| Castelo Branco   | 60              |
| Coimbra          | 65              |
| Évora            | 60              |
| Faro             | 65              |
| Guarda           | 55              |
| Leiria           | 70              |
| Lisboa           | 50              |
| Portalegre       | 60              |
| Porto            | 55              |
| Santarém         | 65              |
| Setúbal          | 60              |
| Viana do Castelo | 65              |
| Vila Real        | 55              |
| Viseu            | 60              |

Table A.2: Possible black soldier fly facilities

| Facility Name    | X Coordinate | Y Coordinate | Inventory Capacity | Production Capacity | Fixed Costs | Processing Costs | Percentage Type A | Percentage Type B | Percentage Type C | Percentage Final Production |
|------------------|--------------|--------------|--------------------|---------------------|-------------|------------------|-------------------|-------------------|-------------------|-----------------------------|
| Aveiro           | 40.6405      | -8.6538      | 25                 | 20                  | 1,500,000   | 400              | 0.25              | 0.25              | 0.25              | 0.8                         |
| Beja             | 38.0151      | -7.8632      | 25                 | 20                  | 1,500,000   | 400              | 0.25              | 0.25              | 0.25              | 0.8                         |
| Braga            | 41.5454      | -8.4265      | 25                 | 20                  | 1,500,000   | 400              | 0.25              | 0.25              | 0.25              | 0.8                         |
| Bragança         | 41.8058      | -6.7572      | 25                 | 20                  | 1,500,000   | 400              | 0.25              | 0.25              | 0.25              | 0.8                         |
| Castelo Branco   | 39.8222      | -7.4909      | 25                 | 20                  | 1,500,000   | 400              | 0.25              | 0.25              | 0.25              | 0.8                         |
| Coimbra          | 40.2115      | -8.4291      | 25                 | 20                  | 1,500,000   | 400              | 0.25              | 0.25              | 0.25              | 0.8                         |
| Évora            | 38.5667      | -7.9000      | 25                 | 20                  | 1,500,000   | 400              | 0.25              | 0.25              | 0.25              | 0.8                         |
| Faro             | 37.0194      | -7.9322      | 25                 | 20                  | 1,500,000   | 400              | 0.25              | 0.25              | 0.25              | 0.8                         |
| Guarda           | 40.5373      | -7.2673      | 25                 | 20                  | 1,500,000   | 400              | 0.25              | 0.25              | 0.25              | 0.8                         |
| Leiria           | 39.7436      | -8.8071      | 25                 | 20                  | 1,500,000   | 400              | 0.25              | 0.25              | 0.25              | 0.8                         |
| Lisbon           | 38.7167      | -9.1390      | 25                 | 20                  | 1,500,000   | 400              | 0.25              | 0.25              | 0.25              | 0.8                         |
| Portalegre       | 39.2938      | -7.4312      | 25                 | 20                  | 1,500,000   | 400              | 0.25              | 0.25              | 0.25              | 0.8                         |
| Porto            | 41.1579      | -8.6291      | 25                 | 20                  | 1,500,000   | 400              | 0.25              | 0.25              | 0.25              | 0.8                         |
| Santarém         | 39.2362      | -8.6861      | 25                 | 20                  | 1,500,000   | 400              | 0.25              | 0.25              | 0.25              | 0.8                         |
| Setúbal          | 38.5244      | -8.8882      | 25                 | 20                  | 1,500,000   | 400              | 0.25              | 0.25              | 0.25              | 0.8                         |
| Viana do Castelo | 41.6946      | -8.8341      | 25                 | 20                  | 1,500,000   | 400              | 0.25              | 0.25              | 0.25              | 0.8                         |
| Vila Real        | 41.3006      | -7.7441      | 25                 | 20                  | 1,500,000   | 400              | 0.25              | 0.25              | 0.25              | 0.8                         |
| Viseu            | 40.6610      | -7.9097      | 25                 | 20                  | 1,500,000   | 400              | 0.25              | 0.25              | 0.25              | 0.8                         |

Table A.3: Possible mealworm facilities

| Facility Name    | X Coordinate | Y Coordinate | Inventory Capacity | Production Capacity | Fixed Costs | Processing Costs | Percentage Type A | Percentage Type B | Percentage Type C | Percentage Final Production |
|------------------|--------------|--------------|--------------------|---------------------|-------------|------------------|-------------------|-------------------|-------------------|-----------------------------|
| Aveiro           | 40.6405      | -8.6538      | 25                 | 20                  | 1,500,000   | 500              | 0.1               | 0.3               | 0.35              | 0.8                         |
| Beja             | 38.0151      | -7.8632      | 25                 | 20                  | 1,500,000   | 500              | 0.1               | 0.3               | 0.35              | 0.8                         |
| Braga            | 41.5454      | -8.4265      | 25                 | 20                  | 1,500,000   | 500              | 0.1               | 0.3               | 0.35              | 0.8                         |
| Bragança         | 41.8058      | -6.7572      | 25                 | 20                  | 1,500,000   | 500              | 0.1               | 0.3               | 0.35              | 0.8                         |
| Castelo Branco   | 39.8222      | -7.4909      | 25                 | 20                  | 1,500,000   | 500              | 0.1               | 0.3               | 0.35              | 0.8                         |
| Coimbra          | 40.2115      | -8.4291      | 25                 | 20                  | 1,500,000   | 500              | 0.1               | 0.3               | 0.35              | 0.8                         |
| Évora            | 38.5667      | -7.9000      | 25                 | 20                  | 1,500,000   | 500              | 0.1               | 0.3               | 0.35              | 0.8                         |
| Faro             | 37.0194      | -7.9322      | 25                 | 20                  | 1,500,000   | 500              | 0.1               | 0.3               | 0.35              | 0.8                         |
| Guarda           | 40.5373      | -7.2673      | 25                 | 20                  | 1,500,000   | 500              | 0.1               | 0.3               | 0.35              | 0.8                         |
| Leiria           | 39.7436      | -8.8071      | 25                 | 20                  | 1,500,000   | 500              | 0.1               | 0.3               | 0.35              | 0.8                         |
| Lisbon           | 38.7167      | -9.1390      | 25                 | 20                  | 1,500,000   | 500              | 0.1               | 0.3               | 0.35              | 0.8                         |
| Portalegre       | 39.2938      | -7.4312      | 25                 | 20                  | 1,500,000   | 500              | 0.1               | 0.3               | 0.35              | 0.8                         |
| Porto            | 41.1579      | -8.6291      | 25                 | 20                  | 1,500,000   | 500              | 0.1               | 0.3               | 0.35              | 0.8                         |
| Santarém         | 39.2362      | -8.6861      | 25                 | 20                  | 1,500,000   | 500              | 0.1               | 0.3               | 0.35              | 0.8                         |
| Setúbal          | 38.5244      | -8.8882      | 25                 | 20                  | 1,500,000   | 500              | 0.1               | 0.3               | 0.35              | 0.8                         |
| Viana do Castelo | 41.6946      | -8.8341      | 25                 | 20                  | 1,500,000   | 500              | 0.1               | 0.3               | 0.35              | 0.8                         |
| Vila Real        | 41.3006      | -7.7441      | 25                 | 20                  | 1,500,000   | 500              | 0.1               | 0.3               | 0.35              | 0.8                         |
| Viseu            | 40.6610      | -7.9097      | 25                 | 20                  | 1,500,000   | 500              | 0.1               | 0.3               | 0.35              | 0.8                         |

Table A.4: Possible domesticus cricket facilities

| Facility Name    | X Coordinate | Y Coordinate | Inventory Capacity | Production Capacity | Fixed Costs | Processing Costs | Percentage Type A | Percentage Type B | Percentage Type C | Percentage Final Production |
|------------------|--------------|--------------|--------------------|---------------------|-------------|------------------|-------------------|-------------------|-------------------|-----------------------------|
| Aveiro           | 40.6405      | -8.6538      | 25                 | 20                  | 1,500,000   | 550              | 0.3               | 0.2               | 0.25              | 0.8                         |
| Beja             | 38.0151      | -7.8632      | 25                 | 20                  | 1,500,000   | 550              | 0.3               | 0.2               | 0.25              | 0.8                         |
| Braga            | 41.5454      | -8.4265      | 25                 | 20                  | 1,500,000   | 550              | 0.3               | 0.2               | 0.25              | 0.8                         |
| Bragança         | 41.8058      | -6.7572      | 25                 | 20                  | 1,500,000   | 550              | 0.3               | 0.2               | 0.25              | 0.8                         |
| Castelo Branco   | 39.8222      | -7.4909      | 25                 | 20                  | 1,500,000   | 550              | 0.3               | 0.2               | 0.25              | 0.8                         |
| Coimbra          | 40.2115      | -8.4291      | 25                 | 20                  | 1,500,000   | 550              | 0.3               | 0.2               | 0.25              | 0.8                         |
| Évora            | 38.5667      | -7.9000      | 25                 | 20                  | 1,500,000   | 550              | 0.3               | 0.2               | 0.25              | 0.8                         |
| Faro             | 37.0194      | -7.9322      | 25                 | 20                  | 1,500,000   | 550              | 0.3               | 0.2               | 0.25              | 0.8                         |
| Guarda           | 40.5373      | -7.2673      | 25                 | 20                  | 1,500,000   | 550              | 0.3               | 0.2               | 0.25              | 0.8                         |
| Leiria           | 39.7436      | -8.8071      | 25                 | 20                  | 1,500,000   | 550              | 0.3               | 0.2               | 0.25              | 0.8                         |
| Lisboa           | 38.7167      | -9.1390      | 25                 | 20                  | 1,500,000   | 550              | 0.3               | 0.2               | 0.25              | 0.8                         |
| Portalegre       | 39.2938      | -7.4312      | 25                 | 20                  | 1,500,000   | 550              | 0.3               | 0.2               | 0.25              | 0.8                         |
| Porto            | 41.1579      | -8.6291      | 25                 | 20                  | 1,500,000   | 550              | 0.3               | 0.2               | 0.25              | 0.8                         |
| Santarém         | 39.2362      | -8.6861      | 25                 | 20                  | 1,500,000   | 550              | 0.3               | 0.2               | 0.25              | 0.8                         |
| Setúbal          | 38.5244      | -8.8882      | 25                 | 20                  | 1,500,000   | 550              | 0.3               | 0.2               | 0.25              | 0.8                         |
| Viana do Castelo | 41.6946      | -8.8341      | 25                 | 20                  | 1,500,000   | 550              | 0.3               | 0.2               | 0.25              | 0.8                         |
| Vila Real        | 41.3006      | -7.7441      | 25                 | 20                  | 1,500,000   | 550              | 0.3               | 0.2               | 0.25              | 0.8                         |
| Viseu            | 40.6610      | -7.9097      | 25                 | 20                  | 1,500,000   | 550              | 0.3               | 0.2               | 0.25              | 0.8                         |

Table A.5: Possible suppliers

| Name                       | X coordinate | Y coordinate | Raw material | Availability | Period | Acquisition Cost |
|----------------------------|--------------|--------------|--------------|--------------|--------|------------------|
| Aveiro                     | 40,6405      | -8,6538      | Watermelon   | 5            | 1      | 150              |
| Aveiro                     | 40,6405      | -8,6538      | Watermelon   | 5            | 2      | 150              |
| Aveiro                     | 40,6405      | -8,6538      | Watermelon   | 5            | 3      | 150              |
| Aveiro                     | 40,6405      | -8,6538      | Watermelon   | 10           | 4      | 150              |
| Aveiro                     | 40,6405      | -8,6538      | Watermelon   | 10           | 5      | 150              |
| Aveiro                     | 40,6405      | -8,6538      | Watermelon   | 10           | 6      | 150              |
| Aveiro                     | 40,6405      | -8,6538      | Watermelon   | 10           | 7      | 150              |
| Aveiro                     | 40,6405      | -8,6538      | Watermelon   | 10           | 8      | 150              |
| Aveiro                     | 40,6405      | -8,6538      | Watermelon   | 10           | 9      | 150              |
| Aveiro                     | 40,6405      | -8,6538      | Watermelon   | 5            | 10     | 150              |
| Aveiro                     | 40,6405      | -8,6538      | Watermelon   | 5            | 11     | 150              |
| Aveiro                     | 40,6405      | -8,6538      | Watermelon   | 5            | 12     | 150              |
| Beja                       | 38,0151      | -7,8632      | Banana       | 5            | 1      | 150              |
| Beja                       | 38,0151      | -7,8632      | Banana       | 5            | 2      | 150              |
| Beja                       | 38,0151      | -7,8632      | Banana       | 5            | 3      | 150              |
| Beja                       | 38,0151      | -7,8632      | Banana       | 10           | 4      | 150              |
| Beja                       | 38,0151      | -7,8632      | Banana       | 10           | 5      | 150              |
| Beja                       | 38,0151      | -7,8632      | Banana       | 10           | 6      | 150              |
| Beja                       | 38,0151      | -7,8632      | Banana       | 10           | 7      | 150              |
| Beja                       | 38,0151      | -7,8632      | Banana       | 10           | 8      | 150              |
| Beja                       | 38,0151      | -7,8632      | Banana       | 10           | 9      | 150              |
| Beja                       | 38,0151      | -7,8632      | Banana       | 5            | 10     | 150              |
| Beja                       | 38,0151      | -7,8632      | Banana       | 5            | 11     | 150              |
| Beja                       | 38,0151      | -7,8632      | Banana       | 5            | 12     | 150              |
| Braga                      | 41,5454      | -8,4265      | Peach        | 5            | 1      | 150              |
| Braga                      | 41,5454      | -8,4265      | Peach        | 5            | 2      | 150              |
| Braga                      | 41,5454      | -8,4265      | Peach        | 5            | 3      | 150              |
| Braga                      | 41,5454      | -8,4265      | Peach        | 10           | 4      | 150              |
| Braga                      | 41,5454      | -8,4265      | Peach        | 10           | 5      | 150              |
| Braga                      | 41,5454      | -8,4265      | Peach        | 10           | 6      | 150              |
| Braga                      | 41,5454      | -8,4265      | Peach        | 10           | 7      | 150              |
| Braga                      | 41,5454      | -8,4265      | Peach        | 10           | 8      | 150              |
| Braga                      | 41,5454      | -8,4265      | Peach        | 10           | 9      | 150              |
| Braga                      | 41,5454      | -8,4265      | Peach        | 5            | 10     | 150              |
| Braga                      | 41,5454      | -8,4265      | Peach        | 5            | 11     | 150              |
| Continues on the next page |              |              |              |              |        |                  |

Table A.5 – Continued from previous page

| Name           | X coordinate | Y coordinate | Raw material | Availability | Period | Acquisition Cost |
|----------------|--------------|--------------|--------------|--------------|--------|------------------|
| Braga          | 41,5454      | -8,4265      | Peach        | 5            | 12     | 150              |
| Bragança       | 41,8058      | -6,7572      | Onion        | 5            | 1      | 100              |
| Bragança       | 41,8058      | -6,7572      | Onion        | 5            | 2      | 100              |
| Bragança       | 41,8058      | -6,7572      | Onion        | 5            | 3      | 100              |
| Bragança       | 41,8058      | -6,7572      | Onion        | 10           | 4      | 100              |
| Bragança       | 41,8058      | -6,7572      | Onion        | 10           | 5      | 100              |
| Bragança       | 41,8058      | -6,7572      | Onion        | 10           | 6      | 100              |
| Bragança       | 41,8058      | -6,7572      | Onion        | 10           | 7      | 100              |
| Bragança       | 41,8058      | -6,7572      | Onion        | 10           | 8      | 100              |
| Bragança       | 41,8058      | -6,7572      | Onion        | 10           | 9      | 100              |
| Bragança       | 41,8058      | -6,7572      | Onion        | 5            | 10     | 100              |
| Bragança       | 41,8058      | -6,7572      | Onion        | 5            | 11     | 100              |
| Bragança       | 41,8058      | -6,7572      | Onion        | 5            | 12     | 100              |
| Castelo Branco | 39,8222      | -7,4909      | Mango        | 5            | 1      | 200              |
| Castelo Branco | 39,8222      | -7,4909      | Mango        | 5            | 2      | 200              |
| Castelo Branco | 39,8222      | -7,4909      | Mango        | 5            | 3      | 200              |
| Castelo Branco | 39,8222      | -7,4909      | Mango        | 10           | 4      | 200              |
| Castelo Branco | 39,8222      | -7,4909      | Mango        | 10           | 5      | 200              |
| Castelo Branco | 39,8222      | -7,4909      | Mango        | 10           | 6      | 200              |
| Castelo Branco | 39,8222      | -7,4909      | Mango        | 10           | 7      | 200              |
| Castelo Branco | 39,8222      | -7,4909      | Mango        | 10           | 8      | 200              |
| Castelo Branco | 39,8222      | -7,4909      | Mango        | 10           | 9      | 200              |
| Castelo Branco | 39,8222      | -7,4909      | Mango        | 5            | 10     | 200              |
| Castelo Branco | 39,8222      | -7,4909      | Mango        | 5            | 11     | 200              |
| Castelo Branco | 39,8222      | -7,4909      | Mango        | 5            | 12     | 200              |
| Coimbra        | 40,2056      | -8,4196      | Pumpkin      | 5            | 1      | 150              |
| Coimbra        | 40,2056      | -8,4196      | Pumpkin      | 5            | 2      | 150              |
| Coimbra        | 40,2056      | -8,4196      | Pumpkin      | 5            | 3      | 150              |
| Coimbra        | 40,2056      | -8,4196      | Pumpkin      | 10           | 4      | 150              |
| Coimbra        | 40,2056      | -8,4196      | Pumpkin      | 10           | 5      | 150              |
| Coimbra        | 40,2056      | -8,4196      | Pumpkin      | 10           | 6      | 150              |
| Coimbra        | 40,2056      | -8,4196      | Pumpkin      | 10           | 7      | 150              |
| Coimbra        | 40,2056      | -8,4196      | Pumpkin      | 10           | 8      | 150              |
| Coimbra        | 40,2056      | -8,4196      | Pumpkin      | 10           | 9      | 150              |
| Coimbra        | 40,2056      | -8,4196      | Pumpkin      | 5            | 10     | 150              |
| Coimbra        | 40,2056      | -8,4196      | Pumpkin      | 5            | 11     | 150              |

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Table A.5 – Continued from previous page

| Name    | X coordinate | Y coordinate | Raw material | Availability | Period | Acquisition Cost |
|---------|--------------|--------------|--------------|--------------|--------|------------------|
| Coimbra | 40,2056      | -8,4196      | Pumpkin      | 5            | 12     | 150              |
| Évora   | 38,5667      | -7,9         | Carrot       | 5            | 1      | 150              |
| Évora   | 38,5667      | -7,9         | Carrot       | 5            | 2      | 150              |
| Évora   | 38,5667      | -7,9         | Carrot       | 5            | 3      | 150              |
| Évora   | 38,5667      | -7,9         | Carrot       | 10           | 4      | 150              |
| Évora   | 38,5667      | -7,9         | Carrot       | 10           | 5      | 150              |
| Évora   | 38,5667      | -7,9         | Carrot       | 10           | 6      | 150              |
| Évora   | 38,5667      | -7,9         | Carrot       | 10           | 7      | 150              |
| Évora   | 38,5667      | -7,9         | Carrot       | 10           | 8      | 150              |
| Évora   | 38,5667      | -7,9         | Carrot       | 10           | 9      | 150              |
| Évora   | 38,5667      | -7,9         | Carrot       | 5            | 10     | 150              |
| Évora   | 38,5667      | -7,9         | Carrot       | 5            | 11     | 150              |
| Évora   | 38,5667      | -7,9         | Carrot       | 5            | 12     | 150              |
| Faro    | 37,0194      | -7,9322      | Pinion       | 5            | 1      | 250              |
| Faro    | 37,0194      | -7,9322      | Pinion       | 5            | 2      | 250              |
| Faro    | 37,0194      | -7,9322      | Pinion       | 5            | 3      | 250              |
| Faro    | 37,0194      | -7,9322      | Pinion       | 10           | 4      | 250              |
| Faro    | 37,0194      | -7,9322      | Pinion       | 10           | 5      | 250              |
| Faro    | 37,0194      | -7,9322      | Pinion       | 10           | 6      | 250              |
| Faro    | 37,0194      | -7,9322      | Pinion       | 10           | 7      | 250              |
| Faro    | 37,0194      | -7,9322      | Pinion       | 10           | 8      | 250              |
| Faro    | 37,0194      | -7,9322      | Pinion       | 10           | 9      | 250              |
| Faro    | 37,0194      | -7,9322      | Pinion       | 5            | 10     | 250              |
| Faro    | 37,0194      | -7,9322      | Pinion       | 5            | 11     | 250              |
| Faro    | 37,0194      | -7,9322      | Pinion       | 5            | 12     | 250              |
| Guarda  | 40,5373      | -7,2658      | Hazelnut     | 5            | 1      | 200              |
| Guarda  | 40,5373      | -7,2658      | Hazelnut     | 5            | 2      | 200              |
| Guarda  | 40,5373      | -7,2658      | Hazelnut     | 5            | 3      | 200              |
| Guarda  | 40,5373      | -7,2658      | Hazelnut     | 10           | 4      | 200              |
| Guarda  | 40,5373      | -7,2658      | Hazelnut     | 10           | 5      | 200              |
| Guarda  | 40,5373      | -7,2658      | Hazelnut     | 10           | 6      | 200              |
| Guarda  | 40,5373      | -7,2658      | Hazelnut     | 10           | 7      | 200              |
| Guarda  | 40,5373      | -7,2658      | Hazelnut     | 10           | 8      | 200              |
| Guarda  | 40,5373      | -7,2658      | Hazelnut     | 10           | 9      | 200              |
| Guarda  | 40,5373      | -7,2658      | Hazelnut     | 5            | 10     | 200              |
| Guarda  | 40,5373      | -7,2658      | Hazelnut     | 5            | 11     | 200              |

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Table A.5 – Continued from previous page

| Name       | X coordinate | Y coordinate | Raw material | Availability | Period | Acquisition Cost |
|------------|--------------|--------------|--------------|--------------|--------|------------------|
| Guarda     | 40,5373      | -7,2658      | Hazelnut     | 5            | 12     | 200              |
| Leiria     | 39,7436      | -8,8071      | Almond       | 5            | 1      | 250              |
| Leiria     | 39,7436      | -8,8071      | Almond       | 5            | 2      | 250              |
| Leiria     | 39,7436      | -8,8071      | Almond       | 5            | 3      | 250              |
| Leiria     | 39,7436      | -8,8071      | Almond       | 10           | 4      | 250              |
| Leiria     | 39,7436      | -8,8071      | Almond       | 10           | 5      | 250              |
| Leiria     | 39,7436      | -8,8071      | Almond       | 10           | 6      | 250              |
| Leiria     | 39,7436      | -8,8071      | Almond       | 10           | 7      | 250              |
| Leiria     | 39,7436      | -8,8071      | Almond       | 10           | 8      | 250              |
| Leiria     | 39,7436      | -8,8071      | Almond       | 10           | 9      | 250              |
| Leiria     | 39,7436      | -8,8071      | Almond       | 5            | 10     | 250              |
| Leiria     | 39,7436      | -8,8071      | Almond       | 5            | 11     | 250              |
| Leiria     | 39,7436      | -8,8071      | Almond       | 5            | 12     | 250              |
| Lisboa     | 38,7167      | -9,1399      | Watermelon   | 5            | 1      | 150              |
| Lisboa     | 38,7167      | -9,1399      | Watermelon   | 5            | 2      | 150              |
| Lisboa     | 38,7167      | -9,1399      | Watermelon   | 5            | 3      | 150              |
| Lisboa     | 38,7167      | -9,1399      | Watermelon   | 10           | 4      | 150              |
| Lisboa     | 38,7167      | -9,1399      | Watermelon   | 10           | 5      | 150              |
| Lisboa     | 38,7167      | -9,1399      | Watermelon   | 10           | 6      | 150              |
| Lisboa     | 38,7167      | -9,1399      | Watermelon   | 10           | 7      | 150              |
| Lisboa     | 38,7167      | -9,1399      | Watermelon   | 10           | 8      | 150              |
| Lisboa     | 38,7167      | -9,1399      | Watermelon   | 10           | 9      | 150              |
| Lisboa     | 38,7167      | -9,1399      | Watermelon   | 5            | 10     | 150              |
| Lisboa     | 38,7167      | -9,1399      | Watermelon   | 5            | 11     | 150              |
| Lisboa     | 38,7167      | -9,1399      | Watermelon   | 5            | 12     | 150              |
| Portalegre | 39,2938      | -7,4312      | Banana       | 5            | 1      | 150              |
| Portalegre | 39,2938      | -7,4312      | Banana       | 5            | 2      | 150              |
| Portalegre | 39,2938      | -7,4312      | Banana       | 5            | 3      | 150              |
| Portalegre | 39,2938      | -7,4312      | Banana       | 10           | 4      | 150              |
| Portalegre | 39,2938      | -7,4312      | Banana       | 10           | 5      | 150              |
| Portalegre | 39,2938      | -7,4312      | Banana       | 10           | 6      | 150              |
| Portalegre | 39,2938      | -7,4312      | Banana       | 10           | 7      | 150              |
| Portalegre | 39,2938      | -7,4312      | Banana       | 10           | 8      | 150              |
| Portalegre | 39,2938      | -7,4312      | Banana       | 10           | 9      | 150              |
| Portalegre | 39,2938      | -7,4312      | Banana       | 5            | 10     | 150              |
| Portalegre | 39,2938      | -7,4312      | Banana       | 5            | 11     | 150              |

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Table A.5 – Continued from previous page

| Name       | X coordinate | Y coordinate | Raw material | Availability | Period | Acquisition Cost |
|------------|--------------|--------------|--------------|--------------|--------|------------------|
| Portalegre | 39,2938      | -7,4312      | Banana       | 5            | 12     | 150              |
| Porto      | 41,1579      | -8,6291      | Peach        | 5            | 1      | 150              |
| Porto      | 41,1579      | -8,6291      | Peach        | 5            | 2      | 150              |
| Porto      | 41,1579      | -8,6291      | Peach        | 5            | 3      | 150              |
| Porto      | 41,1579      | -8,6291      | Peach        | 10           | 4      | 150              |
| Porto      | 41,1579      | -8,6291      | Peach        | 10           | 5      | 150              |
| Porto      | 41,1579      | -8,6291      | Peach        | 10           | 6      | 150              |
| Porto      | 41,1579      | -8,6291      | Peach        | 10           | 7      | 150              |
| Porto      | 41,1579      | -8,6291      | Peach        | 10           | 8      | 150              |
| Porto      | 41,1579      | -8,6291      | Peach        | 10           | 9      | 150              |
| Porto      | 41,1579      | -8,6291      | Peach        | 5            | 10     | 150              |
| Porto      | 41,1579      | -8,6291      | Peach        | 5            | 11     | 150              |
| Porto      | 41,1579      | -8,6291      | Peach        | 5            | 12     | 150              |
| Santarém   | 39,2362      | -8,6857      | Onion        | 5            | 1      | 100              |
| Santarém   | 39,2362      | -8,6857      | Onion        | 5            | 2      | 100              |
| Santarém   | 39,2362      | -8,6857      | Onion        | 5            | 3      | 100              |
| Santarém   | 39,2362      | -8,6857      | Onion        | 10           | 4      | 100              |
| Santarém   | 39,2362      | -8,6857      | Onion        | 10           | 5      | 100              |
| Santarém   | 39,2362      | -8,6857      | Onion        | 10           | 6      | 100              |
| Santarém   | 39,2362      | -8,6857      | Onion        | 10           | 7      | 100              |
| Santarém   | 39,2362      | -8,6857      | Onion        | 10           | 8      | 100              |
| Santarém   | 39,2362      | -8,6857      | Onion        | 10           | 9      | 100              |
| Santarém   | 39,2362      | -8,6857      | Onion        | 5            | 10     | 100              |
| Santarém   | 39,2362      | -8,6857      | Onion        | 5            | 11     | 100              |
| Santarém   | 39,2362      | -8,6857      | Onion        | 5            | 12     | 100              |
| Setúbal    | 38,5244      | -8,8882      | Mango        | 5            | 1      | 200              |
| Setúbal    | 38,5244      | -8,8882      | Mango        | 5            | 2      | 200              |
| Setúbal    | 38,5244      | -8,8882      | Mango        | 5            | 3      | 200              |
| Setúbal    | 38,5244      | -8,8882      | Mango        | 10           | 4      | 200              |
| Setúbal    | 38,5244      | -8,8882      | Mango        | 10           | 5      | 200              |
| Setúbal    | 38,5244      | -8,8882      | Mango        | 10           | 6      | 200              |
| Setúbal    | 38,5244      | -8,8882      | Mango        | 10           | 7      | 200              |
| Setúbal    | 38,5244      | -8,8882      | Mango        | 10           | 8      | 200              |
| Setúbal    | 38,5244      | -8,8882      | Mango        | 10           | 9      | 200              |
| Setúbal    | 38,5244      | -8,8882      | Mango        | 5            | 10     | 200              |
| Setúbal    | 38,5244      | -8,8882      | Mango        | 5            | 11     | 200              |

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Table A.5 – Continued from previous page

| Name             | X coordinate | Y coordinate | Raw material | Availability | Period | Acquisition Cost |
|------------------|--------------|--------------|--------------|--------------|--------|------------------|
| Setúbal          | 38,5244      | -8,8882      | Mango        | 5            | 12     | 200              |
| Viana do Castelo | 41,6918      | -8,8344      | Pumpkin      | 5            | 1      | 150              |
| Viana do Castelo | 41,6918      | -8,8344      | Pumpkin      | 5            | 2      | 150              |
| Viana do Castelo | 41,6918      | -8,8344      | Pumpkin      | 5            | 3      | 150              |
| Viana do Castelo | 41,6918      | -8,8344      | Pumpkin      | 10           | 4      | 150              |
| Viana do Castelo | 41,6918      | -8,8344      | Pumpkin      | 10           | 5      | 150              |
| Viana do Castelo | 41,6918      | -8,8344      | Pumpkin      | 10           | 6      | 150              |
| Viana do Castelo | 41,6918      | -8,8344      | Pumpkin      | 10           | 7      | 150              |
| Viana do Castelo | 41,6918      | -8,8344      | Pumpkin      | 10           | 8      | 150              |
| Viana do Castelo | 41,6918      | -8,8344      | Pumpkin      | 10           | 9      | 150              |
| Viana do Castelo | 41,6918      | -8,8344      | Pumpkin      | 5            | 10     | 150              |
| Viana do Castelo | 41,6918      | -8,8344      | Pumpkin      | 5            | 11     | 150              |
| Viana do Castelo | 41,6918      | -8,8344      | Pumpkin      | 5            | 12     | 150              |
| Vila Real        | 41,3006      | -7,7441      | Carrot       | 5            | 1      | 150              |
| Vila Real        | 41,3006      | -7,7441      | Carrot       | 5            | 2      | 150              |
| Vila Real        | 41,3006      | -7,7441      | Carrot       | 5            | 3      | 150              |
| Vila Real        | 41,3006      | -7,7441      | Carrot       | 10           | 4      | 150              |
| Vila Real        | 41,3006      | -7,7441      | Carrot       | 10           | 5      | 150              |
| Vila Real        | 41,3006      | -7,7441      | Carrot       | 10           | 6      | 150              |
| Vila Real        | 41,3006      | -7,7441      | Carrot       | 10           | 7      | 150              |
| Vila Real        | 41,3006      | -7,7441      | Carrot       | 10           | 8      | 150              |
| Vila Real        | 41,3006      | -7,7441      | Carrot       | 10           | 9      | 150              |
| Vila Real        | 41,3006      | -7,7441      | Carrot       | 5            | 10     | 150              |
| Vila Real        | 41,3006      | -7,7441      | Carrot       | 5            | 11     | 150              |
| Vila Real        | 41,3006      | -7,7441      | Carrot       | 5            | 12     | 150              |
| Viseu            | 40,661       | -7,9097      | Pinion       | 5            | 1      | 250              |
| Viseu            | 40,661       | -7,9097      | Pinion       | 5            | 2      | 250              |
| Viseu            | 40,661       | -7,9097      | Pinion       | 5            | 3      | 250              |
| Viseu            | 40,661       | -7,9097      | Pinion       | 10           | 4      | 250              |
| Viseu            | 40,661       | -7,9097      | Pinion       | 10           | 5      | 250              |
| Viseu            | 40,661       | -7,9097      | Pinion       | 10           | 6      | 250              |
| Viseu            | 40,661       | -7,9097      | Pinion       | 10           | 7      | 250              |
| Viseu            | 40,661       | -7,9097      | Pinion       | 10           | 8      | 250              |
| Viseu            | 40,661       | -7,9097      | Pinion       | 10           | 9      | 250              |
| Viseu            | 40,661       | -7,9097      | Pinion       | 5            | 10     | 250              |
| Viseu            | 40,661       | -7,9097      | Pinion       | 5            | 11     | 250              |

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Table A.5 – Continued from previous page

| Name           | X coordinate | Y coordinate | Raw material | Availability | Period | Acquisition Cost |
|----------------|--------------|--------------|--------------|--------------|--------|------------------|
| Viseu          | 40,661       | -7,9097      | Pinion       | 5            | 12     | 250              |
| Aveiro         | 40,6405      | -8,6538      | Hazelnut     | 5            | 1      | 200              |
| Aveiro         | 40,6405      | -8,6538      | Hazelnut     | 5            | 2      | 200              |
| Aveiro         | 40,6405      | -8,6538      | Hazelnut     | 5            | 3      | 200              |
| Aveiro         | 40,6405      | -8,6538      | Hazelnut     | 10           | 4      | 200              |
| Aveiro         | 40,6405      | -8,6538      | Hazelnut     | 10           | 5      | 200              |
| Aveiro         | 40,6405      | -8,6538      | Hazelnut     | 10           | 6      | 200              |
| Braga          | 41,5454      | -8,4265      | Watermelon   | 5            | 1      | 150              |
| Braga          | 41,5454      | -8,4265      | Watermelon   | 5            | 2      | 150              |
| Braga          | 41,5454      | -8,4265      | Watermelon   | 5            | 3      | 150              |
| Braga          | 41,5454      | -8,4265      | Watermelon   | 10           | 4      | 150              |
| Braga          | 41,5454      | -8,4265      | Watermelon   | 10           | 5      | 150              |
| Braga          | 41,5454      | -8,4265      | Watermelon   | 10           | 6      | 150              |
| Bragança       | 41,8058      | -6,7572      | Banana       | 10           | 7      | 150              |
| Bragança       | 41,8058      | -6,7572      | Banana       | 10           | 8      | 150              |
| Bragança       | 41,8058      | -6,7572      | Banana       | 10           | 9      | 150              |
| Bragança       | 41,8058      | -6,7572      | Banana       | 5            | 10     | 150              |
| Bragança       | 41,8058      | -6,7572      | Banana       | 5            | 11     | 150              |
| Bragança       | 41,8058      | -6,7572      | Banana       | 5            | 12     | 150              |
| Beja           | 38,0151      | -7,8632      | Almond       | 10           | 7      | 250              |
| Beja           | 38,0151      | -7,8632      | Almond       | 10           | 8      | 250              |
| Beja           | 38,0151      | -7,8632      | Almond       | 10           | 9      | 250              |
| Beja           | 38,0151      | -7,8632      | Almond       | 5            | 10     | 250              |
| Beja           | 38,0151      | -7,8632      | Almond       | 5            | 11     | 250              |
| Beja           | 38,0151      | -7,8632      | Almond       | 5            | 12     | 250              |
| Castelo Branco | 39,8222      | -7,4909      | Peach        | 5            | 1      | 150              |
| Castelo Branco | 39,8222      | -7,4909      | Peach        | 5            | 2      | 150              |
| Castelo Branco | 39,8222      | -7,4909      | Peach        | 5            | 3      | 150              |
| Castelo Branco | 39,8222      | -7,4909      | Peach        | 10           | 4      | 150              |
| Castelo Branco | 39,8222      | -7,4909      | Peach        | 10           | 5      | 150              |
| Castelo Branco | 39,8222      | -7,4909      | Peach        | 10           | 6      | 150              |
| Coimbra        | 40,2056      | -8,4196      | Onion        | 10           | 7      | 100              |
| Coimbra        | 40,2056      | -8,4196      | Onion        | 10           | 8      | 100              |
| Coimbra        | 40,2056      | -8,4196      | Onion        | 10           | 9      | 100              |
| Coimbra        | 40,2056      | -8,4196      | Onion        | 5            | 10     | 100              |
| Coimbra        | 40,2056      | -8,4196      | Onion        | 5            | 11     | 100              |

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Table A.5 – Continued from previous page

| Name    | X coordinate | Y coordinate | Raw material | Availability | Period | Acquisition Cost |
|---------|--------------|--------------|--------------|--------------|--------|------------------|
| Coimbra | 40,2056      | -8,4196      | Onion        | 5            | 12     | 100              |

Table A.6: Relation matrix between the different raw materials and their types

| Material   | Vegetal | Fruit | Dry fruits |
|------------|---------|-------|------------|
| Pumpkin    | 1       | 0     | 0          |
| Almond     | 0       | 0     | 1          |
| Hazelnut   | 0       | 0     | 1          |
| Banana     | 0       | 1     | 0          |
| Onion      | 1       | 0     | 0          |
| Carrot     | 1       | 0     | 0          |
| Mango      | 0       | 1     | 0          |
| Watermelon | 0       | 1     | 0          |
| Peach      | 0       | 1     | 0          |
| Pinion     | 0       | 0     | 1          |

Table A.7: Conversion ratios of the different raw materials for the different insects

| Material   | Black soldier fly | Mealworm | Domesticus cricket |
|------------|-------------------|----------|--------------------|
| Pumpkin    | 0,774             | 0,936    | 0,958              |
| Almond     | 0,667             | 0,728    | 0,614              |
| Hazelnut   | 0,997             | 0,580    | 0,855              |
| Banana     | 0,973             | 0,624    | 0,639              |
| Onion      | 0,942             | 0,960    | 0,607              |
| Carrot     | 0,994             | 0,807    | 0,565              |
| Mango      | 0,926             | 0,556    | 0,583              |
| Watermelon | 0,682             | 0,948    | 0,743              |
| Peach      | 0,559             | 0,881    | 0,802              |
| Pinion     | 0,855             | 0,849    | 0,548              |

Table A.8: Fixed costs variation with the districts

| Facility name    | Fixed Costs |
|------------------|-------------|
| Aveiro           | 1500000     |
| Beja             | 1200000     |
| Braga            | 1500000     |
| Bragança         | 1200000     |
| Castelo Branco   | 1200000     |
| Coimbra          | 1500000     |
| Évora            | 1200000     |
| Faro             | 1500000     |
| Guarda           | 1200000     |
| Leiria           | 1500000     |
| Lisboa           | 2000000     |
| Portalegre       | 1200000     |
| Porto            | 2000000     |
| Santarém         | 1200000     |
| Setúbal          | 1500000     |
| Viana do Castelo | 1200000     |
| Vila Real        | 1200000     |
| Viseu            | 1200000     |

## Appendix B

## Results

Table B.1: Costs evolution for the different scenarios

| Iteration | Costs              |                    |                       |                                       |
|-----------|--------------------|--------------------|-----------------------|---------------------------------------|
|           | Baseline scenario  | 1 restriction      | Different fixed Costs | 1 restriction + different fixed costs |
| 1         | $4,96 \times 10^6$ | $4,91 \times 10^6$ | $5,96 \times 10^6$    | $5,91 \times 10^6$                    |
| 2         | $4,95 \times 10^6$ | $4,90 \times 10^6$ | $4,36 \times 10^6$    | $4,61 \times 10^6$                    |
| 3         | $4,95 \times 10^6$ | $4,90 \times 10^6$ | $4,07 \times 10^6$    | $4,30 \times 10^6$                    |
| 4         | $4,95 \times 10^6$ | $4,89 \times 10^6$ | $4,05 \times 10^6$    | $4,01 \times 10^6$                    |
| 5         | $4,94 \times 10^6$ | $4,89 \times 10^6$ | $4,05 \times 10^6$    | $4,00 \times 10^6$                    |
| 6         | $4,94 \times 10^6$ | $4,89 \times 10^6$ | $4,04 \times 10^6$    | $3,99 \times 10^6$                    |
| 7         | $4,94 \times 10^6$ | $4,89 \times 10^6$ | $4,04 \times 10^6$    | $3,99 \times 10^6$                    |
| 8         | $4,94 \times 10^6$ | $4,89 \times 10^6$ | $4,04 \times 10^6$    | $3,99 \times 10^6$                    |
| 9         | $4,94 \times 10^6$ | $4,88 \times 10^6$ | $4,04 \times 10^6$    | $3,98 \times 10^6$                    |
| 10        | $4,94 \times 10^6$ | $4,88 \times 10^6$ | $4,04 \times 10^6$    | $3,98 \times 10^6$                    |

Table B.2: Emissions evolution for the different scenarios

| Iteration | Emissions         |               |                       |                                       |
|-----------|-------------------|---------------|-----------------------|---------------------------------------|
|           | Baseline scenario | 1 restriction | Different fixed Costs | 1 restriction + different fixed costs |
| 1         | 72,60             | 66,77         | 72,60                 | 66,76                                 |
| 2         | 79,63             | 72,36         | 84,27                 | 75,98                                 |
| 3         | 86,65             | 77,96         | 95,93                 | 85,19                                 |
| 4         | 93,68             | 83,56         | 107,60                | 94,41                                 |
| 5         | 100,71            | 89,16         | 119,26                | 103,62                                |
| 6         | 107,74            | 94,76         | 130,93                | 112,84                                |
| 7         | 114,76            | 100,36        | 142,60                | 122,05                                |
| 8         | 121,79            | 105,96        | 154,26                | 131,27                                |
| 9         | 128,82            | 111,55        | 165,93                | 140,48                                |
| 10        | 135,85            | 117,15        | 177,60                | 149,70                                |