Network Design of an Insect-based Supply Chain

Miguel Fernando Nunes Teixeira Borba

Masters Dissertation

Supervisor: Dr. Maria João Martins dos Santos

U. PORTO

FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

Masters in Mechanical Engineering

2023-06-26

Abstract

Insect farming has recently gained notoriety as a more sustainable alternative in the food and feed industry. Legislative changes allowed the use of insect-derived protein as livestock feed, which offers significant advantages over conventional livestock production methods. Insects need less land, water, and feed than conventional livestock and can be fed on residual by-products from the food transformation industry that would otherwise be considered waste. In addition, their digestive tracts emit minimal amounts of methane unlike ruminants, and are highly efficient in absorbing nutrients. By capitalizing on these factors, insect farming demonstrates a substantially smaller environmental footprint compared to conventional protein sources like cattle rearing and intensive agriculture.

The location of an insect-rearing plant constitutes a facility location problem that is affected by several factors. This dissertation presents a linear cost-minimizing model that considers factors like transportation costs from the suppliers and to consumers, processing costs, and fixed costs that may include, land, labor, and capital costs. The presented model is flexible being able to be used in a variety of insect-based supply chains, for different products, insects, feed materials, production processes, and scale of operation.

Resumo

A criação de insetos recentemente ganhou notoriedade como uma alternativa sustentável na indústria agropecuária. Alterações na legislação permitiram o uso de proteínas derivadas de insetos como alimentação para gado, esta prática oferece vantagens significativas sobre a pecuária tradicional. Os insetos requerem menos terreno, água e alimento do que o gado tradicional, para além de poderem ser alimentados com subprodutos da indústria alimentar que de outro modo seriam considerados resíduos. O sistema digestivo dos insetos emite mínimas quantidades de metano, em oposição aos ruminantes e são eficientes a absorber nutrientes. Capitalizando nestes fatores a criação de insetos demonstra uma pegada ecológica significativamente inferior à de fontes convencionais de proteína tais como a pecuária e agricultura intensiva.

A localização de uma fábrica de criação de insetos constitui um problema de localização de instalações que é afetado por vários fatores. Esta dissertação apresenta um modelo linear de minimização de custos que considera fatores como custos de transporte dos fornecedores e para os consumidores, custos de processamento, custos fixos, que podem incluir imobiliário, mão de obra e custos de capital. O modelo apresentado é flexível, podendo ser utilizado em vários tipos de cadeias de abastecimento que utilizem insetos, para diferentes produtos finais, insetos, matérias primas, processos produtivos e escala de operação.

Acknowledgements

I want to acknowledge everyone who directly or indirectly made this work possible.

I want to acknowledge Plano de Recuperação e Resiliência (PRR) for sponsoring the project in which this dissertation is a part of.

First I would like to thank my supervisor, Dr. Maria João Santos who guided me in this project, was always available to help and encouraged me to accomplish my objectives.

To Dr. Sara Martins for her knowledgeable insights and suggestions.

To my parents for their unconditional love and support even in the toughest moments, for giving me the conditions to pursue my studies, and to believe in me even when I didn't believe in myself.

To all my friends who helped me relax from work and make my life worth living.

To Inês, who has been with me for over 11 years and has always kept in touch, to all those long talks where we shared our struggles and motivated each other.

To Vanda, that alongside being a great friend, helped me find a small programming mistake that gave me a big headache.

And finally to my grandparents who are no longer here to witness this moment but will always be an enormous part of my life and who I am as a person. To my grandfather that never doubted me and to my grandmother for instilling in me the importance of hard work.

Contents

1 Introduction **1**
1.1 Project framework and motivation 1
1.2 Project InsectERA 2
1.3 Objetives 2
1.4 Methodology followed in the project 3
1.5 Structure of the document 3

2 Literature review **4**
2.1 Insect-based industry 4
2.1.1 Legal context 4
2.1.2 Frass 6
2.1.3 Insect life cycle 6
2.1.4 Aplications 7
2.2 Facility location problem 9

3 Presentation and modeling of the problem **11**
3.1 Input parameters 11
3.2 Decision variables 14
3.3 Objective function 15
3.4 Constraints 16

4 Model runs and discussion **17**
4.1 Input data 17
4.2 Base scenario 18
4.3 Different acquisition costs 20
4.4 Substrates 21
4.4.1 Same costs 21
4.4.2 Different processing costs 21
4.5 Fixed costs 22
4.6 Taking customers into account 24
4.6.1 Product customers only 24
4.6.2 Product and frass customers 26
4.7 Seasonality 27
4.8 2 Plants 28
4.9 Example scenario 29
4.10 Transport cost analysis 30

5 Conclusion and future work **31**

References **32**

A Appendix A - Results of the model runs **35**

Acronyms and Symbols

BSF	Black soldier fly
FLP	Facility location problem
PAP	Processed animal protein
PRR	Plano de Recuperação e Resiliência

List of Figures

2.1 Summary table of legal status for applications of insect-derived products 5
2.2 Life cycle of BSF, in Smet et al. (2018) 7
2.3 Diagram of the supply chain of an insect-based product in IPFF (2022) 8

4.1 Supplier and plant locations 19
4.2 Supplier, plant, and customer locations 24
4.3 Supplier, plant, product customer and frass customer locations 26

List of Tables

4.1 Sumary of input parameters for the model runs 18
4.2 Distance Matrix d_{ij} [km] between suppliers and plants 18
4.3 Distance Matrix d_{jk} [km] between plants and product customers 18
4.4 Distance Matrix d_{jl} [km] between plants and frass customers 18
4.5 Costs for scenario 4.2 20
4.6 Acquisition costs (Ca_i) for scenario 4.3 20
4.7 Costs for scenario 4.3 20
4.8 Conversion ratios (Cr_s) for scenario 4.4.1 21
4.9 Costs for scenario 4.4.1 21
4.10 Processing costs (cp_s) for scenario 4.4.2 21
4.11 Costs for scenario 4.4.2 22
4.12 Fixed costs (cf_j) for scenario 4.5 22
4.13 Costs for scenario 4.5 23
4.14 Costumer demand (D_k) 24
4.15 Costs for scenario 4.6.1 25
4.16 Frass customers maximum capacity ($Mfcust_l$) 27
4.17 Costs for scenario 4.6.2 27
4.18 Substrate availability from suppliers ($Msup_{sit}$) in scenario 4.7 27
4.19 Costs for scenario 4.7 28
4.20 Costs for scenario 4.8 28
4.21 Substrate availability from suppliers ($Msup_{sit}$) in scenario 4.9 29
4.22 Acquisition cost of substrate (Ca_{sit}) in scenario 4.9 29
4.23 Costs for scenario 4.9 29
4.24 Costs for scenario 4.10 30
4.25 Summary table of all model runs 30

Chapter 1

Introduction

In this chapter, there is a presentation of this dissertation and the project in which it is integrated, including contextualization and background that justifies its relevance. The objectives of the project are explained and there is a summary of the methodology used for the elaboration of this work and an overview of the document structure.

1.1 Project framework and motivation

The ever-pressing matter of trying to achieve greater sustainability combined with the growing food needs of the world population has led to a push into finding alternative ways of producing food. The agriculture and livestock industry has a significant environmental impact in factors such as land use, erosion of soils, water use, use of chemical fertilizers, and greenhouse gas emissions among others (Steinfeld et al., 2006; Qian et al., 2018; Ritchie et al., 2022).

Insect-derived products have several applications, one of the more promising ones is their use as animal feed. Animal feed represents a very large industry and insect-derived protein could help replace soy which is currently one of the staples of protein in animal feed. This soy is mostly transgenic and cultivated in an intensive way, in monoculture, and using chemical fertilizers and pesticides (Tallentire et al., 2018).

One of the ways to provide alternative food sources is by using insects. Insects can be fed on waste materials of low value, and produce protein-rich insect meat that can either be directly consumed by humans or used to feed animals for human consumption. Insects are ectothermic and therefore use little energy to maintain their body temperature (Broeckx et al., 2021), and have a more efficient digestive system than cattle, which means it is possible to obtain more protein per kg of feed, comprising a higher bioconversion ratio. This, combined with the fact that insects can be fed byproducts of other industries that would otherwise be waste means that insect meat has a much lower environmental impact than traditional meat from livestock, in terms of methane, ammonia, and carbon dioxide emissions, land use, water consumption, and waste generation (Oonincx et al., 2010).

This work was done in INESC-TEC as part of the InsectERA project encompassing several research centers and industry partners with the objective of developing insect-based technologies, industries, and products. One of the focus points in the project is identifying the best locations to deploy the industry. This work constitutes a mathematical optimization model capable of choosing a location with the lowest costs based on the parameters given.

1.2 Project InsectERA

InsectERA is a project co-financed by PRR (Plan of Recovery and Resilience), the Portuguese application of the NextGenerationEU, the European plan that allocates funds to projects that allow countries to make their economies stronger and more sustainable, to be more prepared for the ecological transition. Insect-based industries are a part of this program because they generate a variety of products with added value produced from materials that would otherwise be considered waste, enabling a circular economy (Madau et al., 2020), reducing waste and CO_2 emissions.

InsectERAs's plan has 4 main axes which compromise the kinds of insect-based industries to be developed:

- INFood: Production of food for human consumption.
- InFeed: Production of animal feed.
- InIndustry: Use of insect-derived substances to be used as raw materials for the cosmetic and pharmaceutical industry.
- InBioremediation: Use of insects as cleaning agents in cases of contamination/pollution of soils, water, waste.

As a result of InsectERA, there is already an R&D center and a plant operating, Entogreen in Santarém, using black soldier flies to produce 3000 t/year of insect protein and oil (Entogreen, nd).

1.3 Objetives

The first objective of this work is to create an optimization model dedicated to locating insect-rearing plants. By considering multiple factors, such as the availability of resources, access to customers, land values, and processing costs, the model will provide a systematic approach to selecting optimal locations for establishing insect-rearing facilities. This model will serve as a valuable decision-making tool for the network design of any insect-based supply chain.

The second objective focuses on testing the developed optimization model in different scenarios. Simulated scenarios made to emulate reality will be employed to evaluate the model's performance and demonstrate its possibilities. By subjecting the model to various situations, we can gain insights into its ability to handle diverse conditions and determine its reliability as a practical solution.

1.4 Methodology followed in the project

Initially, there was literature research on the topic of insect farming with the objective of knowing the particularities of this industry, its advantages and limitations, legal context, sustainability, and important factors that may affect it. This was followed by a literature review on the theme of facility location problems with the purpose of knowing alternatives to solve and model the problem.

Then an initial model was drafted and tested with a fictional set of data using the solver capabilities of Microsoft Office Excell. After confirming the model's success, it was programmed using Python package pulp. The initial model was then progressively modified with added capabilities to better be able to model the real-life situation.

After the model had been chosen, research was done to create a set of fictional data that would better resemble a real scenario, including data on costs, distance matrices, and maps. With this data, several scenarios were created to test the model in order to highlight its capabilities and compare results. The tests were run followed by the registering and discussion of the results.

1.5 Structure of the document

In chapter 2 there is a literature review to give contextualization of the subject of insect farming, including its applications, specificities, and legal framing, as well as facility location problems in general. In chapter 3 the problem is presented and the mathematical model is provided, with the definition of all variables, sets, inputs, outputs, objective function, and constrains. In chapter 4 the model is tested in several different scenarios, the model parameters are presented, the scenarios are explained and the results are discussed. In chapter 5 there is a conclusion and a presentation of possible future works to build on this study.

Chapter 2

Literature review

This section provides a literature review of two relevant topics for the contextualization of this work, the insect-based industry and the facility location problems.

2.1 Insect-based industry

2.1.1 Legal context

Previously, European and local laws did not allow for the use of insect-derived feed to be given to animals destined for human consumption. Much of the legislation that forbade the use of animal products as livestock feed (European Parliament, Council of the EU, 2001) stemmed from the outbreak of bovine spongiform encephalopathy during the 1980s and 1990s which is believed to be caused by the feeding of animal-derived products to cows, namely meat and bone meal. Studies (van Raamsdonk et al., 2017) conducted more recently had proven that such risks are very low in the case of insect-derived products and as such the legislation was progressively altered to allow for its use. EU Regulation European Parliament, Council of the EU (2017) first allowed for insect-derived products to be used as fish feed in aquaculture and for pet feed. In April 2021, the EU Member States voted positively on the authorization of insect-processed animal proteins (PAPs) in poultry and pig feed (European Parliament, Council of the EU, 2021). In Figure 2.1 can be seen an overall summary of the state of European legislation regarding insect-based products to be used as animal feed.

Insects as feed - **Regulation (EU) No 68/2013** on the Catalogue of feed materials and in accordance **with Regulation (EC) No 999/2001 and Regulation (EC) No 1069/2009**	Ruminant animals	Aquaculture	Poultry	Pigs	Pets	Fur and other animals (e.g. zoo)	Technical uses(e.g. cosmetic industry, bio-based fuels, production of other bio-based materials such as bioplastics)
Insect proteins (under entry 9.4.1. 'Processed animal protein')	✗	✓ **	✓ **	✓ **	✓	✓	✓
Insect fats (under entry 9.2.1 'animal fat')	✓	✓	✓	✓	✓	✓	✓
Whole insects (untreated) (under entry 9.16.2. 'terrestrial invertebrates, dead')	✗	✗	✗	✗	✓ ***	✓ ***	✓
Whole insects (treated- e.g. Freeze drying) (under entry 9.16.2.'terrestrial invertebrates, dead')	✗	✗	✗	✗	✓ ***	✓ ***	✓
Live insects (under entry 9.16.1 'terrestrial invertebrates, live')	✗	✓ *	✓ *	✓ *	✓ ***	✓ ***	✓
Hydrolysed insect proteins (under entry 9.6.1. 'Hydrolysed animal proteins')	✓	✓	✓	✓	✓	✓	✓

Figure 2.1: Summary table of legal status for applications of insect-derived products in IPFF (2022)
* If authorized by the national competent authority
** Limited to selected species (detailed below)
*** If authorized by the national competent authority in case the product is intended for use as processed pet food

Currently, after some successive addictions, this is the list of species of insects that are allowed to be used in insect farms for the production of livestock feed:

- Black Solider Fly (*Hermetia illucens*)
- Common Housefly (*Musca domestica*)
- House Cricket (*Acheta domesticus*)
- Banded Cricket (*Gryllodes sigillatus*)
- Field Cricket (*Gryllus assimilis*)
- Yellow Mealworm (*Tenebrio molitor*)
- Lesser Mealworm (*Alphitobius diaperinus*)
- Silkworm (*Bombyx mori*)

The kind of material to be used as insect feed, in this work referred as *substrate*, is also regulated in European Parliament, Council of the EU (2009) which states that only materials of plant origin can be used as feed. There are some exceptions such as dairy and some processed waste. The feeding of farmed animals with slaughterhouse or rendering derived products, manure, or catering/ kitchen waste is however prohibited. The same ban applies to the use of unsold products from supermarkets or food industries. Mostly the kinds of substrates used are vegetable-based byproducts from the food transformation industry, such as:

- Spent brewer grains (byproduct of beer production)
- Olive pomace (byproduct of olive oil production)
- Grape pomace (byproduct of wine production)
- Vegetable waste from food processing (mostly unused parts of vegetables)

2.1.2 Frass

Frass is a subproduct of insect farming that consists of undigested substrate and insect feces, it is in mass the largest output of the insect industry. This organic material serves as a nutrient-rich fertilizer, offering various benefits for plant growth and soil health. Frass contains a variety of organic matter, such as cellulose, chitin, proteins, and other nutrients that were present in the original substrate (Beesigamukama et al., 2022; Poveda, 2021). Additionally, it may also contain microbial populations from the insect's digestive system. According to Yildirim-Aksoy et al. (2020) frass also demonstrated it can be used as fish feed. Its sustainable and eco-friendly nature makes it a promising option for organic agriculture and gardening. The use of insect frass as a fertilizer has been permitted since the modification of the EU Regulation 142/2011 (European Parliament, Council of the EU, 2011), which included insect frass in a new category named "insect excrements", with the requirement that frass that is to be used as fertilizer has to be subjected to heat treatment at 70 °C for 60 min.

2.1.3 Insect life cycle

The life cycle of the insects generally follows a similar pattern although there are specific variations for each insect. The life cycle of the BSF is depicted in Figure 2.2 as an illustrative example. Adult insects mate and subsequently lay eggs, which eventually hatch into larvae. These larvae feed on a substrate until they reach a stage where they are ready to form a pupa. After a period of pupating, adult insects emerge from the pupae (Smet et al., 2018). In the context of food and feed applications, the fully grown larvae are harvested due to their high nutritional value. This practice offers both economic and environmental benefits because larvae exhibit rapid growth rates and their digestive systems efficiently absorb nutrients. It is important to note that if all larvae are harvested, there will be no adults left to lay new eggs. Therefore, insect production necessitates an egg-producing section where the larvae can undergo transformation into adults capable of mating and laying eggs.

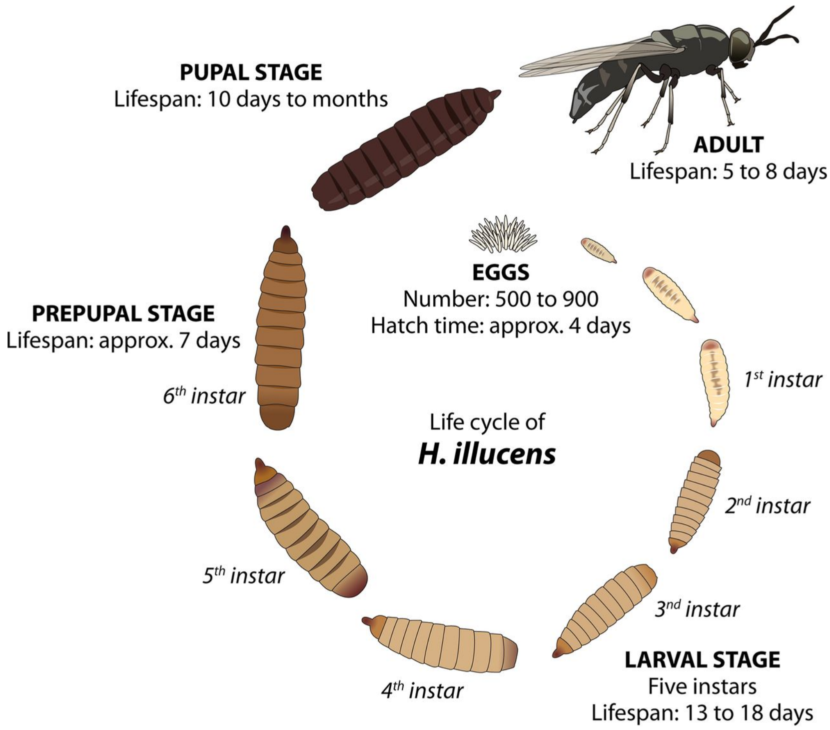

Figure 2.2: Life cycle of BSF, in Smet et al. (2018)

2.1.4 Aplications

There is an array of different products that can be made using insects, each with its applications and several ways of organizing the supply chain. In this section, the products and their supply chain will be discussed.

Live insects can be used to feed livestock directly. Using the live insects is a simple solution as it doesn't require any special processing equipment, however, this solution is usually only used in small-scale productions as the live insects are harder to transport and have a very limited shelf life. It is also harder for the livestock breeder to mix it into its feed in the correct proportion.

It is more common in large-scale operations the use of processed animal proteins (PAP), which can be obtained from a variety of processes, such as freezing, heating, sterilizing, drying and grinding the insects, resulting in a dehydrated powder or granular product which is easy to transport and has a long shelf life. It is sold to animal feed manufacturers that can easily mix it in adequate proportions.

Non-alimentary industries can use insect-derived materials. Chitin, a substance present in adult insect exoskeletons can be extracted from insects and used on pharmaceutical and cosmetic products (Aranaz et al., 2018; Kulka and Sionkowska, 2023). In addition chitin and be processed into chitosan which is a polymeric material, in essence, a bioplastic, providing an alternative to petrol-based plastics (Rehman et al., 2023).

The cleaning of contaminants such as heavy metals from soil, water, waste, or even antibiotics (Liu et al., 2021) can also be accomplished by means of insects in a process called bioremediation. In this application insects digest the contaminated matter and retain the contaminants in their bodies, concentrating the contaminants and making their disposal simple. Insects can be used with the purpose of processing organic waste (Diener et al., 2011). According to Bulak et al. (2021) insects have demonstrated capabilities to decompose plastics, presenting a solution to the plastic waste problem.

Figure 2.3 illustrates a simplified diagram of a possible supply chain of insect-derived products.

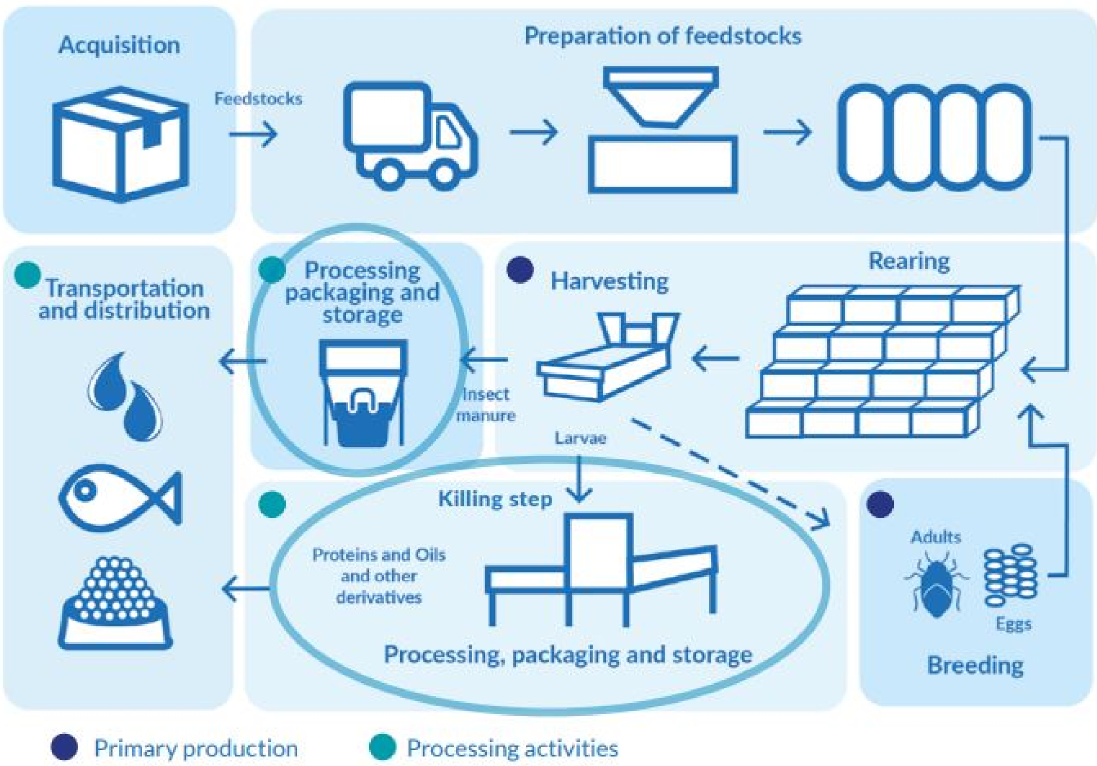

Figure 2.3: Diagram of the supply chain of an insect-based product in IPFF (2022)

2.2 Facility location problem

A facility location problem (FLP) involves determining the optimal location of facilities such as warehouses, manufacturing plants, and distribution centers to minimize costs and improve the efficiency of the supply chain. There are several different ways to solve this problem, considering different factors and varying levels of complexity. In this section, there will be a characterization of the kinds of FLP.

There are two approaches to solving a FLP, continuous and discrete. The continuous FLP assumes that facilities can be located anywhere on a map, whereas the discrete space FLP assumes that new facilities will be selected among a pre-identified set of possible locations. Occasionally both can be used sequentially, being the continuous option used for a first approach, and then selected locations can be compared directly on a discrete approach (Carlo et al., 2017). The discrete problem is the one idolized in this work and has the benefit of allowing some pre-screening of available locations (excluding for instance locations where there isn't space, or there are concerns of the locals such as smell or contaminants), however identifying possible locations constitutes additional work that needs to be done when compared to a continuous model.

Regarding discrete models, one of the simpler methods is known as the center of gravity. In this method, only transport costs are considered and the model will choose the solution which minimizes the distance traveled by the vehicles carrying goods. This method is relatively simple to calculate as it only requires to be known the physical locations of the origins and destinations of the goods, so it can be used, for instance, as a first approximation on more elaborate models (Ballou, 1973).
FLPs can also be divided in 2 categories: capacitated and uncapacitated. In the capacitated FLP the plants' maximum capacity is limited, while in the uncapacitated problem it is assumed to be unlimited (Sridharan, 1995). The present work constitutes a capacitated problem as the plants have a maximum capacity.

One way to solve a FLP is to model it numerically, frequently the economic side of the problem is modeled, so there is an objective function that can calculate profits to be maximized, or costs to be minimized. A set of variables must be created which will be the output of the model. In such a cost model the typical objective for the FLP is to minimize the total cost, typically associated with fixed (e.g., investment) and variable (e.g., transportation) costs (Carlo et al., 2012). A set of constraints must be set to represent the real-life limitations of the problem, such as plant capacities, mathematical relations between variables, etc. In order to solve the problem the model can be programmed and run on a solver. There are several sorts of solvers which are algorithms designed to find a solution to the problem, adequate to different sorts of models.

Suckling et al. (2021) is one of the more similar works to this one found in the literature. This article presents a cost model for an industry of animal feed made of insect meat. Specifically, the industry in focus uses BSF as the insect and spent brewer grains as substrate. The insect-rearing units are small modular units to be placed near the substrate suppliers. The purpose of the model is to compare the costs of 3 different production chain arrangements, one where live insects are directly fed to livestock, one where each insect-rearing facility processes its insects into PAP, and one where there is a central processing unit. The cost model in Suckling et al. (2021) is similar to the one presented in this work in the fact that transport costs are calculated based on distances and mass transported as well as the inclusion of fixed costs. However, it is very different in the core purpose of the model which in the case of the present work is to locate facilities as opposed to comparing supply chain options. It is also of note that the model presented in the referred article is designed around a pre-established industry, not featuring the adaptability of the model being proposed in this work, for instance by not considering different insects, substrates, customers, and seasonality, among others.

Chapter 3

Presentation and modeling of the problem

In the following chapter, the model developed is presented and explained, including the definition of its parameters, sets, objective function, variables, and constraints.

The purpose of the presented model is to choose the optimal location or locations for an insect farm with the aim of minimizing total costs. This result is indicated by the variable y_j, that represents which plant(s) the model has chosen to open.

3.1 Input parameters

Since the production chains that use insects can be very diversified the model was built to be able to cover a wide range of situations, it is however assumed that a plant or a cluster of plants receive substrate to feed the insects, have a main final output, here referred as *product*, consumed by *costumers*. There may be a secondary output named *frass* that is consumed by *frass customers*.

The desired production capacity of the plants must be chosen prior to running the model and given as an input ($Mplant_j$). When such a choice is made the fixed cost of operating a plant (cf_j) must adequately reflect the maximum capacity since a higher maximum capacity requires a bigger plant with more machinery and staff, thus having higher costs. The cf_j input reflects the fixed costs of operating a plant and can be calculated by including factors such as fixed labor costs, taxes, insurance, energy costs, construction costs, land costs and capital costs, adequately annualized. These factors can be different for each potential location (j) because of different land values, local taxes and labor costs or local climate which may alter energy costs however, it is possible to use the same value for all potential locations, thus excluding these factors from the calculation. It is possible to attribute different plant capacities for each location j in order to test for combinations of different plant sizes or to accommodate specific requirements of the location such as available space or workforce. If a limit on the number of plants open is required "n_plant" must be defined a priori. Otherwise removing completely this parameter allows the model to choose the optimal number of plants.

By imposition of the model, customer demand (D_k) must be satisfied, so when formulating the problem, care must be exerted so that only customers that are to be served are included. There must be sufficient plant capacity ($Mplant_j$) and supplier capacity ($Msup_{sit}$) to satisfy customer demand. Conversely, supplier capacity can be unlimited, i.e. if there is more than needed the model will still run.

Transportation costs are calculated by the product of the mass to be transported (x, z, h) divided by the average load of a vehicle (vc), an estimated cost per km of purchasing and operating a vehicle (ct), and the distance traveled by the vehicles (d). As such the vehicle capacities must be chosen having in mind the scale of the operation (larger operations use larger vehicles). The potential locations of facilities and customers must be given in order to generate the distance matrices.
The model admits the use of different vehicles for the 3 types of material being transported (substrate, product, and frass). However, the same vehicle can be used, in which case the parameters vc and ct all have the same values.

Ratios

The substrate conversion ratio (Cr) represents the portion of the insect feed that becomes insect meat once the insects are collected, thus can be calculated as expressed in equation (3.1).

$$Cr = \frac{\text{mass of insects}}{\text{mass of substrate}} \tag{3.1}$$

The frass conversion ratio (Crf) represents the portion of the insect feed that becomes frass as expressed in equation (3.2):

$$Crf = \frac{\text{mass of frass}}{\text{mass of substrate}} \tag{3.2}$$

Since frass is made up of the insect fecal matter and undigested substrate it is the part of the substrate that does not become insect meat (m_substrate = m_insects + m_frass). It is possible to calculate the Crf from Cr as expressed in equation (3.3).

$$Crf = 1 - Cr \tag{3.3}$$

The process ratio (Pr) represents the portion in mass of insects that will become the final product as represented in equation (3.4). Processes such as drying reduce the moisture consent, and thus the mass of the final product. If the final product is the insects without any mass altering post-processing Pr = 1

$$Pr = \frac{\text{mass of final product}}{\text{mass of insects}} \tag{3.4}$$

The model admits a set of suppliers of substrate, each supplier may have one or several different substrates available. Cost and availability can be specified by supplier, substrate and time. The set time is included to accommodate the possibility of seasonality in the availability of substrates so it allows to divide the year which is the time horizon used by the model into any number of times eg. 1 for constant, 4 being one for each season, 12 being one for each month. It is considered that the output of the plants is constant and storage of substrate or product is not considered. Since the production is assumed constant there is no point in storing it, storage of the substrate is not used in view of the relatively long periods of seasonality considered and the fact that substrate degrades over time. The duration of a period depends on the number of periods (f), duration [days]=$\frac{365}{f}$ so the values for its availability ($Msup_{sit}$) are given for each period.

It is possible that such detailed data may not be available, and thus is possible, to run the model without seasonality (f=1), just one substrate (u=1), the same values of acquisition for every supplier, and the same fixed cost for every plant. In this case, the model reverts to a center of gravity location problem.

There is the possibility of placing a facility adjacent to an already existing plant, for instance placing it adjacent to a food processing plant in order to minimize the transport costs for the insect feed. In such a situation the food waste from the plant can be transported by pipeline or by conveyor belt. It is possible to accommodate this situation on the model, by introducing 0 as the distance between the supplier and the plant in the respective d_{ij}, the calculated transport cost from the supplier to the plant will be 0. Also, there are some cases where waste heat from an adjacent building (like a data center) is used for the climate control needed in an insect-rearing facility, thus reducing energy costs.

Sets

I	=	{1, ..., n}	set of suppliers
J	=	{1, ..., m}	set of plants
K	=	{1, ..., w}	set of product customers
L	=	{1, ..., l}	set of frass customers
T	=	{1, ..., f}	set of times
S	=	{1, ..., u}	set of substrates

Parameters

$vc1$	[t]	maximum capacity of vehicle type 1, used for deliveries of substrate
$vc2$	[t]	maximum capacity of vehicle type 2, used for deliveries of product
$vc3$	[t]	maximum capacity of vehicle type 3, used for deliveries of frass
$ct1$	[€/km]	cost of owning and operating vehicle type 1
$ct2$	[€/km]	cost of owning and operating vehicle type 2
$ct3$	[€/km]	cost of owning and operating vehicle type 3
ca_{sit}	[€/t]	acquisition cost of substrate s from supplier i in period t
cp_s	[€/t]	processing cost of substrate s
d_{ij}	[€/t]	distance matrix between suppliers and pants
d_{jk}	[€/t]	distance matrix between plants and product customers
d_{jl}	[€/t]	distance matrix between plants and frass customers
cf_j	[€]	fixed cost of operating plant j
Cr_s		conversion ratio of substrate s
Crf_s		frass conversion ratio of substrate s
Pr		processing ratio
$Msup_{sit}$	[t]	availability of substrate s from supplier i in period t
$Mplant_j$	[t]	production capacity of plant j (of product)
$Mfcust_l$	[t]	maximum capacity of frass customer l
D_k	[t]	demand of product from customer k
f		number of seasonality periods
n_plant		maximum number of plants to locate

3.2 Decision variables

$x_{ijts} \in \mathbb{R}_{\geq 0}$ - [t] mass of substrate s transported and purchased from supplier i to plant j in the time t

$$y_j = \begin{cases} 0, & \text{plant j is not being used} \\ 1, & \text{plant j is being used} \end{cases}$$

$z_{jk} \in \mathbb{R}_{\geq 0}$ - [t] mass of product produced in plant j and transported to customer k

$h_{jl} \in \mathbb{R}_{\geq 0}$ - [t] mass of frass produced in plant j and transported to frass customer l

3.3 Objective function

The objective function minimizes total costs and is given by the sum of the terms (3.5)-(3.10) as follows.

$$\sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\sum_{s\in S}(x_{ijts}\cdot Ca_{sit}) \tag{3.5}$$

$$+\sum_{i\in I}\sum_{j\in J}\left(\sum_{t\in T}\sum_{s\in S}x_{ijts}\cdot\frac{ct1}{vc1}\cdot d_{ij}\right) \tag{3.6}$$

$$+\sum_{j\in J}\sum_{k\in K}\left(z_{jk}\cdot\frac{ct2}{vc2}\cdot d_{jk}\right) \tag{3.7}$$

$$+\sum_{j\in J}\sum_{k\in K}\left(h_{jl}\cdot\frac{ct3}{vc3}\cdot d_{jl}\right) \tag{3.8}$$

$$+\sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\sum_{s\in S}(x_{ijts}\cdot cp_s) \tag{3.9}$$

$$+\sum_{j\in J}(y_j\cdot cf_j) \tag{3.10}$$

Term (3.5) represents the acquisition costs of the substrate, while this is assumed to be a cost by default, it can be an income in the case the supplier pays to have the substrate disposed of, in that case Ca_{sit} has a negative value.

Term (3.6) represents the transportation costs of the substrate from its suppliers to the plants. The cost is the product of the quantity of substrate transported (x_{ijts}), the distance between supplier and plant (d_{ij}), and the cost of operating the vehicle (vc1) divided by its capacity (vc1).

Term (3.7) represents the transportation costs of the product from the plants to its customers. The cost is the product of the quantity of product transported (z_{jk}), the distance between plant and customer (d_{jk}), and the cost of operating the vehicle (vc2) divided by its capacity (vc2).

Term (3.8) represents the transportation costs of the frass from the plants to the frass customers. The cost is the product of the quantity of frass transported (h_{jl}), the distance between plant and customer (d_{jl}), and the cost of operating the vehicle (vc3) divided by its capacity (vc3).

Term (3.9) represents the pre-processing costs of each substrate.

Term (3.10) represents the fixed costs of having an open plant.

3.4 Constraints

The set of the problem's constraints is as follows:

$$\sum_{j\in J} x_{ijts} \leq Msup_{sit} \qquad \forall i\in I,\ t\in T,\ s\in S \tag{3.11}$$

$$\sum_{k\in K} z_{jk} \leq Mplant_j \cdot y_j \qquad \forall j\in J \tag{3.12}$$

$$\sum_{k\in K} h_{jl} \leq Mfcust_l \qquad \forall j\in J \tag{3.13}$$

$$\sum_{j\in J} z_{jk} = D_k \qquad \forall k\in K \tag{3.14}$$

$$\sum_{i\in I}\sum_{t\in T}\sum_{s\in S}(x_{ijts}\cdot Cr_s\cdot Pr) = \sum_{k\in K} z_{jk} \qquad \forall j\in J \tag{3.15}$$

$$\sum_{i\in I}\sum_{t\in T}\sum_{s\in S}(x_{ijts}\cdot Crf_s) = \sum_{l\in L} h_{jl} \qquad \forall j\in J \tag{3.16}$$

$$\sum_{i\in I}\sum_{s\in S}(x_{ijts}\cdot Cr_s\cdot Pr) = \sum_{k\in K} z_{jk}/f \qquad \forall j\in J,\ t\in T \tag{3.17}$$

$$\sum_{j\in J} y_j \leq n\_plant \tag{3.18}$$

$$x_{ijts}, z_{jk}, h_{jl} \geq 0 \tag{3.19}$$

$$y_j \in \{0,1\} \tag{3.20}$$

Equation (3.11) sets the maximum availability of substrate from the suppliers.

Equation (3.12) sets the maximum capacity of the plants and defines binary variable y_j.

Equation (3.13) sets the maximum capacity of the frass customers.

Equation (3.14) imposes the demand from customers.

Equation (3.15) imposes the conversion ratios Cr_s and Pr in order to define variable z_{jk} which depends on variable x_{ijts} and the ratios.

Equation (3.16) imposes the conversion ratio Crf_f in order to define variable h_{jl} which depends on variable x_{ijts} and the ratios.

Equation (3.17) guarantees that the total purchasing (from all suppliers) of each factory is constant every period, thus allowing for constant production.

Equation (3.18) limits the maximum number of plants to be opened. The restriction can be changed from $\leq$ to = in order to impose the number of plants.

Equation (3.19) guarantees that all continuous variables are non negative.

Equation (3.20) guarantees that variable y can only take the binary values of 0 and 1.

Chapter 4

Model runs and discussion

In this chapter, several test runs of the proposed model are made, in different hypothetical scenarios to illustrate the capabilities of the model. The input data for the cases is not real, such as the locations of plants, suppliers, and customers but the parameter values are based on reality so that the obtained results can be similar to the ones obtained on a real case.

The model was implemented using the "Pulp" package of Python programming language. Since the model is linear all results are absolute, because the objective function has no local minimums. All runs of the model were almost immediate, taking just a few seconds.

4.1 Input data

When available, the input data was collected from the literature as follows:

- vc: 20t - average capacity of a large articulated freight truck (Volvotrucks, nd)
- ct: 1.52 €/km - calculated assuming a 180 000€ initial vehicle cost (Europa-Camioes.com, nd), annualized over 10 years, fuel consumption of 40l/100km, fuel cost of 1.5€/l, 200km per day, driver salary of 1500€ per month, assuming such driver does 200km/day for 221 days per year. 0.2€/km for maintenance, 2000€/year for insurance and 500€/year for taxes.
- Cr of insect feed for the kind of insects used for commercial applications most common values are between 0.17-0.50 (Bava et al., 2019; Jin et al., 2022; Mannaa et al., 2024)
- Pr: 0.30 - assumed a process of drying of the insects which reduces its moisture content from 70% to 10% (Suckling et al., 2021)
- Mj: 3000 t/year - taken from Entogreen plant in Santarém (Entogreen, nd)
- cf: 1 609 000 € calculated assuming 13.7 million € from Entogreen's (Nunes, 2022) initial cost project, annualized over 20 years and assuming 55 workers with an average pay of 1200€/month

Table 4.1 summarizes the values referred to previously that will be used on the model runs presented in this chapter unless specific indication of different values being used.

Table 4.1: Sumary of input parameters for the model runs

parameter	value
vc1	20
vc2	20
vc3	20
ct1	1.52
ct2	1.52
ct2	1.52
ca	0
cp	5
Cr	0.25
Pr	0.30
Mj	3000
cf	1 609 000

The maps represented in Figures 4.1-4.3 were generated using Mapcreator tool.
The distance matrices considered in the model runs were generated using Route Matrix API, from Geroapify are as follows in Tables 4.2-4.4:

i\j	1	2	3	4
1	0.6	19	7	8
2	3	21	9	10
3	16	5	20	8
4	17	2	13	7

Table 4.2: Distance Matrix d_{ij} [km] between suppliers and plants

j\k	1	2	3	4
1	0.5	21	55	10
2	18	3	72	18
3	7	19	61	4
4	8	7	62	10

Table 4.3: Distance Matrix d_{jk} [km] between plants and product customers

j\l	1	2	3	4
1	10	17	12	17
2	1	25	14	2
3	4	11	4	15
4	10	17	9	7

Table 4.4: Distance Matrix d_{jl} [km] between plants and frass customers

4.2 Base scenario

This case illustrates one of the most basic versions of the model and it will serve as a comparison with the other cases shown ahead. In this case, the only deciding factor is the location of the suppliers since all other factors are the same: same cf, Cr, ca, $Mplant_j$, $Msup_{sit}$. There is no seasonality, so there is a single time, f=1 which corresponds to the entire year and there is a single substrate that is offered by all the suppliers, so there is a single Cr and cp.
The supplier and plant locations are shown in Figure 4.1. For this case, customer locations are not considered, in order to not consider customers the parameter vc2 must be set to 0, thus making all transportation costs to customers 0. Since for the resolution of the problem the model needs customer demand (Mk), the pretended product output can be entirely applied to a single "virtual" customer, the distance of this customer to the locations (l_ij) is irrelevant since all transport costs

are set to 0. Frass is not taken into account so Crf_s must be all set to 0, thus ensuring there is no frass production to be considered by the model.

Figure 4.1: Supplier and plant locations

In this scenario, the chosen plant location was 1. There is an excess in the supplier capacity, total supplier capacity = $4 \times 12\ 500 = 50\ 000$, and the demand for substrate is $\frac{3000}{0.25 \times 0.30}$ =40 000 so the model is able to choose which supplier not to use fully. Since the chosen plant location is 1, the supplier that is farther is the one that is not fully used, i=4. The existence of this excess capacity makes it so that the chosen location may not be the one whose average distance from all the suppliers is the lowest, since not all suppliers are idolized the same. The chosen location is the one whose average distance multiplied by the flow of goods is the lowest. Besides making an academic point of comparison with other versions, the possibility of running such a simplified version of the model can be useful in a pre-planning stage where more detailed data about potential customers or substrates is unknown. Table 4.5 presents the cost structure of the optimal solution.

Table 4.5: Costs for scenario 4.2

Acquisition cost	0
Transport cost substrate	21 850
Transport cost product	0
Transport cost frass	0
Fixed plant cost	1 609 000
Pre-processing cost	200 000
Total cost	1 830 850

4.3 Different acquisition costs

In this case, the base scenario remains the same, except that there are now varying acquisition costs for the substrate from each supplier which are displayed in Table 4.6

Table 4.6: Acquisition costs (Ca_i)

i	Ca_i
1	38
2	35
3	32
4	30

As can be seen on Table 4.7 the acquisition costs represent a very significant part of the overall costs (42%) thus the model minimized them by avoiding the most expensive supplier (1) as much as possible. Location 4 was chosen as with the reduced importance of supplier 1 it had the most favorable distance for all suppliers.

Table 4.7: Costs for scenario 4.3

Acquisition cost	1 307 500
Transport cost substrate	25 270
Transport cost product	0
Transport cost frass	0
Fixed plant cost	1 609 000
Pre-processing cost	171 875
Total cost	3 141 770

4.4 Substrates

4.4.1 Same costs

This scenario is identical to the base scenario (4.2) with the alteration that now several different substrates are considered, with different Cr, seen in Table 4.8. In this example, each supplier provides a different substrate.

Table 4.8: Conversion ratios (Cr_s)

s	Cr_s
1	0.15
2	0.20
3	0.35
4	0.30

The selected location is 4. The model will favor the suppliers which have substrates with higher Cr, in this scenario, suppliers 3 and 4. Using a higher Cr substrate means that less substrate is needed to produce the same amount of product, thus reducing substrate transportation and pre-processing costs. Suppliers 3 and 4 are fully used, supplier 2 is not fully used and supplier 1 is not used at all. Because of this, the model will prioritize the locations which have the shortest distances to suppliers 3 and 4, then supplier 2, and not consider distance supplier 1. Table 4.9 presents the cost structure of the optimal solution.

Table 4.9: Costs for scenario 4.4.1

Acquisition cost	0
Transport cost substrate	21 375
Transport cost product	0
Transport cost frass	0
Fixed plant cost	1 609 000
Pre-processing cost	171 875
Total cost	1 802 250

4.4.2 Different processing costs

Here the same conversion ratios from scenario 4.4.1 were used, but the substrates were given different processing costs (cp_s), as illustrated in Table 4.10.

Table 4.10: Processing costs (cp_s)

s	cp_s
1	7
2	8
3	2
4	3

The selected plant location is 4, the same as the previous scenario despite the fact that the processing costs favored location 2 by having the cheaper suppliers (3 and 4) closer to it. This happened because the demand for substrate is sufficiently high that 9375t of substrate still has to be supplied by supplier 1, which tips the more favorable plant location in favor of 4. Table 4.11 presents the cost structure of the optimal solution.

Table 4.11: Costs for scenario 4.4.2

Acquisition cost	0
Transport cost substrate	21 375
Transport cost product	0
Transport cost frass	0
Fixed plant cost	1 609 000
Pre-processing cost	137 500
Total cost	1 767 875

4.5 Fixed costs

This scenario is identical to the base scenario, with the difference that now the fixed plant costs (cf_j) vary for each location j as shown in Table 4.12.
Data:

Table 4.12: Fixed costs (cf_j)

j	cf_j
1	1 616 000
2	1 604 000
3	1 600 000
4	1 608 000

The selected location is 4. Now two different costs are considered, the fixed cost and substrate transport cost. Since this problem uses the same distance matrices as the base scenario it is already established that the location which minimizes substrate transport cost is j=1, with a cost of 21 850€. In contrast, location j=1 is the one with the highest fixed cost. The model chose location y=3 as it has the lowest fixed cost, despite its transportation cost (31 350€) being higher than location 1. This happens because the higher transport cost is completely compensated by a lower fixed cost:

$$31\,350 - 21\,850 = 9\,500 < 16\,000 = 1\,616\,000 - 1\,600\,000$$

Table 4.13 presents the cost structure of the optimal solution.

Table 4.13: Costs for scenario 4.5

Acquisition cost	0
Transport cost substrate	31 350
Transport cost product	0
Transport cost frass	0
Fixed plant cost	1 600 000
Pre-processing cost	200 000
Total cost	1 831 350

4.6 Taking customers into account

4.6.1 Product customers only

In this scenario, customers are considered so there is a customer demand D_k, in Table 4.14 below. ct2 now is not 0, but takes the same value as ct1, 1.52, as it is assumed the same type of vehicle is used. Figure 4.2 shows the locations of the customers in addition to the already presented supplier and plant locations. Customer 3 is not shown as it is located farther away in the northwest direction, about 55km from the closest plant location (1).

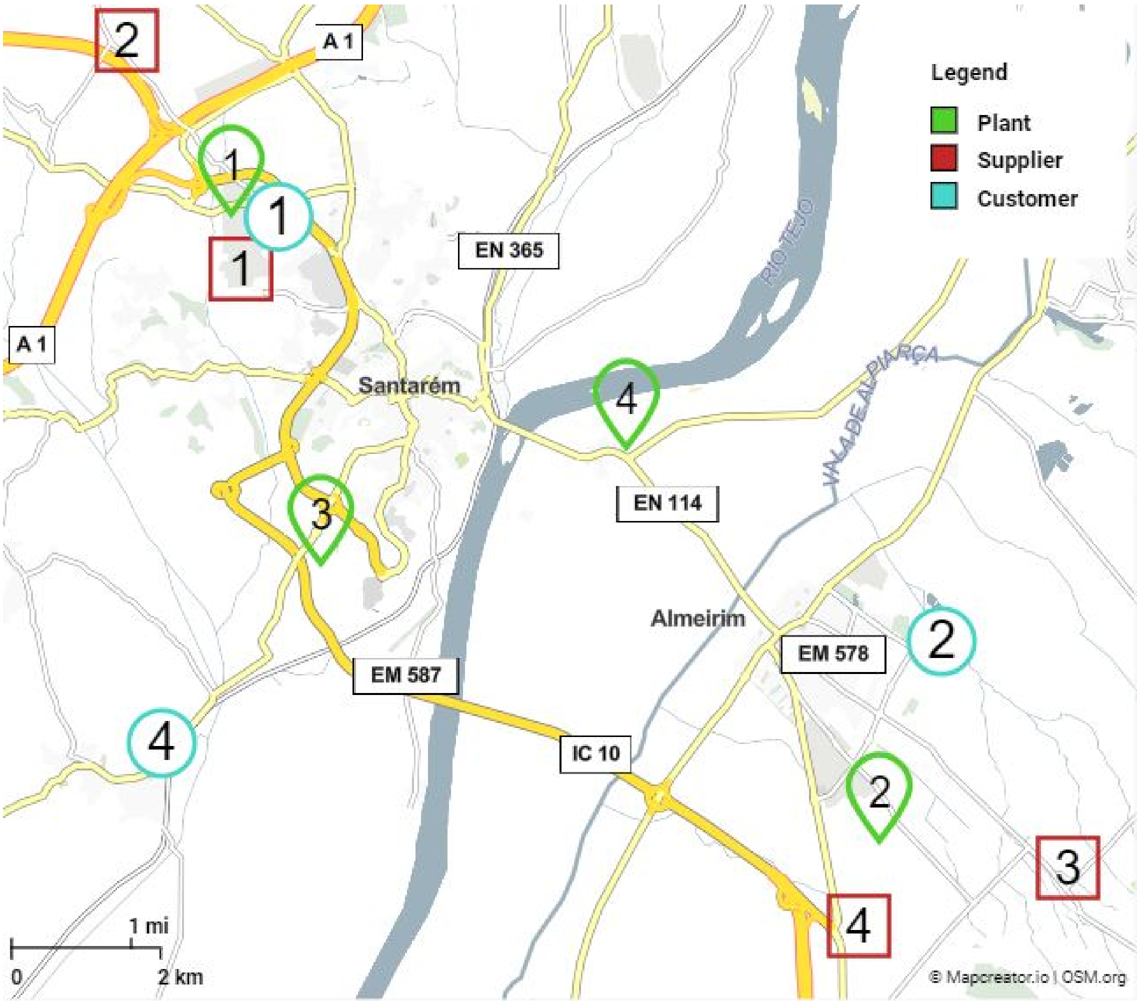

Figure 4.2: Supplier, plant, and customer locations

Table 4.14: Costumer demand (D_k)

k	D_k
1	100
2	2 000
3	300
4	600

In this scenario, there are two transport costs in analysis, substrate and product. The model will choose the option which minimizes the total cost, in this scenario, plant 4 was chosen because of its central location between customers which minimizes product transport cost that is sufficient to compensate for an increase in the substrate transport cost vs the base scenario as seen below:

$$23\ 750 - 2\ 994 = 20\ 756 \leq 21\ 850$$

Table 4.15 presents the cost structure of the optimal solution.

Table 4.15: Costs for scenario 4.6.1

Acquisition cost	0
Transport cost substrate	23 750
Transport cost product	2 994
Transport cost frass	0
Fixed plant cost	1 609 000
Pre-processing cost	200 000
Total cost	1 835 744

4.6.2 Product and frass customers

This instance is built upon scenario 4.6.1 but now frass production and distribution are considered. ct3 is set at 1.52, assuming the same vehicle type is used for all transport. Frass conversion ratios were calculated according to equation 3.3. The location of the frass customer can be seen on Figure 4.3 and their maximum purchasing capability is shown on Table 4.16.

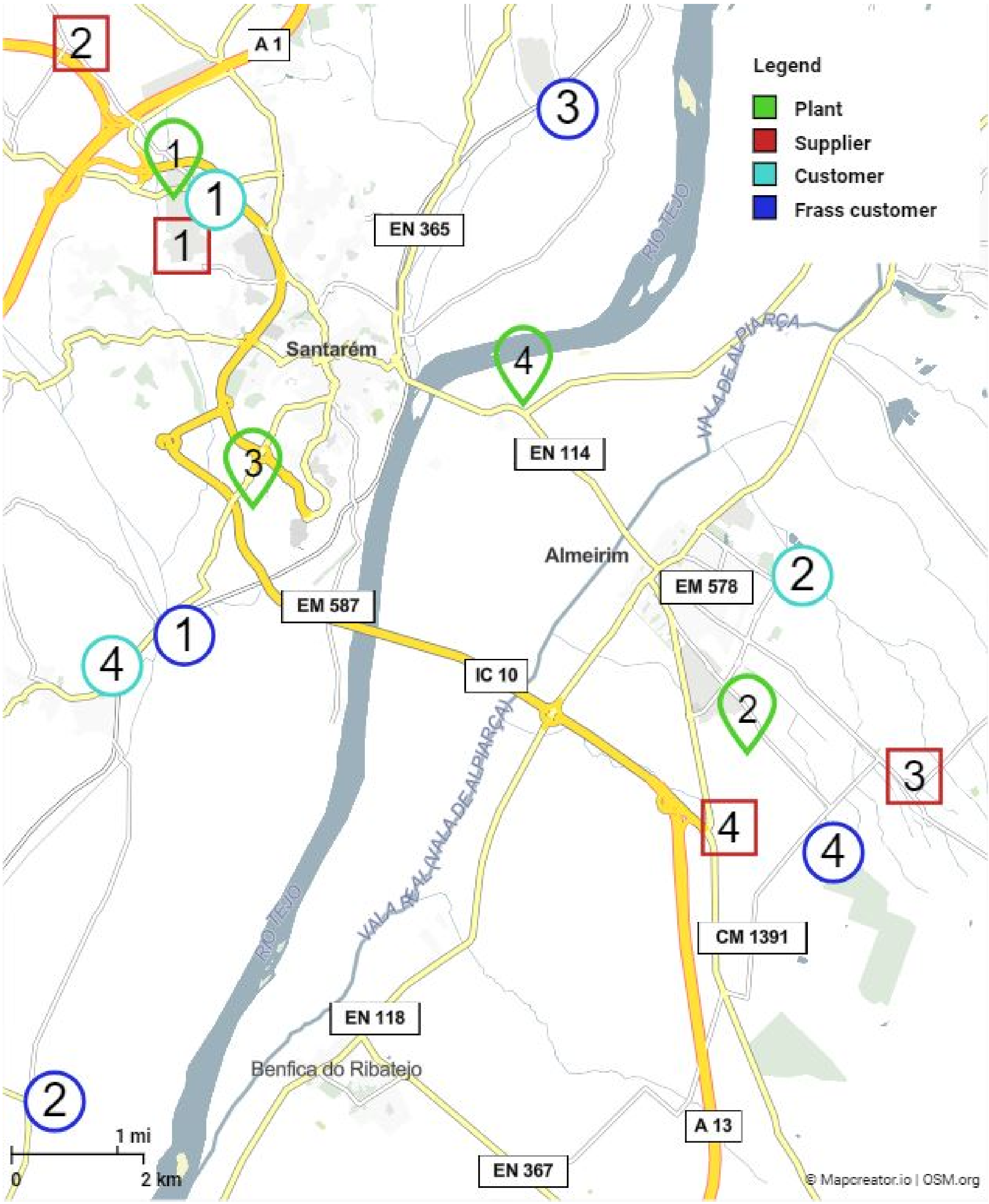

Figure 4.3: Supplier, plant, product customer and frass customer locations

Table 4.16: Frass customers maximum capacity ($Mfcust_l$)

l	M_l
1	10 000
2	10 000
3	10 000
4	10 000

The chosen location is 4, because the model now considers 3 transportation costs, substrate, product, and frass, and location 4 is closer to the frass customers than location 1.
Due to the way the conversion ratios work, the amount of frass generated is considerably superior to the amount of product produced, meaning that the cost of frass transport represents a higher portion of the total costs than product transport. This constitutes another incentive for the model to prioritize higher Cr, since the higher the Cr, the lower the Crf, so less frass will have to be transported for the same amount of product delivered. Table 4.17 presents the cost structure of the optimal solution.

Table 4.17: Costs for scenario 4.6.2

Acquisition cost	0
Transport cost substrate	28 690
Transport cost product	3 055
Transport cost frass	12 920
Fixed plant cost	1 609 000
Pre-processing cost	200 000
Total cost	1 853 665

4.7 Seasonality

In this scenario, seasonality in the availability of substrate is considered. The year is divided into two 6 months periods (t=1 and t=2). The values for the availability of the substrate are shown below in Table 4.18. The values were chosen so that the total yearly availability from all suppliers is the same as the base scenario (50 000 t).

Table 4.18: Substrate availability from suppliers ($Msup_{sit}$)

i	t	$Msup_{sit}$	i	t	$Msup_{sit}$
1	1	6 250	1	2	0
2	1	6 250	2	2	4 000
3	1	6 250	3	2	8 000
4	1	6 250	4	2	13 000

The selected location is 2 because the limited availability of substrate forced the model to resort to different suppliers vs the base scenario (4.2). In the season t=2, due to the increased availability of suppliers 3 and 4 it was possible to use them exclusively, which favored location 2 which is the one closest to them. Table 4.19 presents the cost structure of the optimal solution.

Table 4.19: Costs for scenario 4.7

Acquisition cost	0
Transport cost substrate	19 931
Transport cost product	0
Transport cost frass	0
Fixed plant cost	1 609 000
Pre-processing cost	200 000
Total cost	1 853 665

4.8 2 Plants

In this scenario, it was studied the case of building 2 smaller plants instead of a single larger one. The plant capacity ($Mplant_j$) is 1500 t, half of what is used in the base scenario, fixed costs (cf) are adjusted to 810 000 € which is over half of the 1 609 000 € of the base scenario to reflect the loss of economies of scale.

As it can be observed in Table 4.20, when compared to the base scenario, the total cost of having 2 plants is lower (1 827 030 vs 1 830 850) due to a much lower transport cost (7 030 vs 21 850), derived from the fact that in this arrangement each plant is only served by the suppliers closer to it, reducing the distance traveled. It should be noted that building more plants can be more expensive if the loss of economies of scale is greater (the fixed costs diminish in a lower proportion than the plant capacity).

Table 4.20: Costs for scenario 4.8

Acquisition cost	0
Transport cost substrate	7 030
Transport cost product	0
Transport cost frass	0
Fixed plant cost	1 620 000
Pre-processing cost	200 000
Total cost	1 827 030

4.9 Example scenario

This example case combines all the features of the previous scenarios to showcase the real capabilities of the model. The locations of the suppliers, plants, customers, and frass customers are the same as in previous cases. There are several substrates and such as in case 4.7 there are 2 seasons. The conversion ratios for the substrates are the same as in case 4.4.1, and their availability from the suppliers is shown in Table 4.21. Processing costs for the substrates are the same as in case 4.4.2 fixed costs are the same as in case 4.5. The costs for the substrate from each supplier can be seen in Table 4.22. Table 4.23 presents the cost structure of the optimal solution.

Table 4.21: Substrate availability from suppliers ($Msup_{sit}$)

s	i	t	$Msup_{sit}$	s	i	t	$Msup_{sit}$
1	1	1	6 250	1	1	2	0
2	2	1	6 250	2	2	2	4 000
3	3	1	6 250	3	3	2	8 000
4	4	1	6 250	4	4	2	13 000

Table 4.22: Acquisition cost of substrate (Ca_{sit})

s	i	t	Ca_{sit}	s	i	t	Ca_{sit}
1	1	1	38	1	1	2	-
2	2	1	35	2	2	2	28
3	3	1	32	3	3	2	30
4	4	1	30	4	4	2	40

Table 4.23: Costs for scenario 4.9

Acquisition cost	1 068 895
Transport cost substrate	14 960
Transport cost product	3 055
Transport cost frass	4 962
Fixed plant cost	1 609 000
Pre-processing cost	162 604
Total cost	2 867 478

The chosen plant location is 2, as a result of the consideration of all previously mentioned factors.

4.10 Transport cost analysis

This scenario is identical to 4.9, but the vehicles used for transport were now assumed to be smaller trucks with a maximum load of 2 t and an adequately adjusted operating cost. The new vehicle data can be seen below:

- vc: 2t - capacity of a small truck
- ct: 0.75 €/km - calculated assuming a 40 000€ initial vehicle cost (Europa-Camioes.com, nd), annualized over 10 years, fuel consumption of 10 l/100km, fuel cost of 1.5€/l, 200km per day, driver salary of 1500€ per month, assuming such driver does 200km/day for 221 days per year. 0.05€/km for maintenance, 2000€/year for insurance and 500€/year for taxes.

As it can be seen in Table 4.24 the transportation costs increased almost five-fold in relation to case 4.9, thus becoming a more significant portion of the total costs. The selected location is 2.

Table 4.24: Costs for scenario 4.10

Acquisition cost	1 068 895
Transport cost substrate	73 820
Transport cost product	15 075
Transport cost frass	24 484
Fixed plant cost	1 609 000
Pre-processing cost	162 604
Total cost	2 953 879

Summary

In Table 4.25 can be seen a summary of the output of all the model runs.

Table 4.25: Summary table of all model runs

Scenario	Selected location(s)
4.2	1
4.3	4
4.4.1	4
4.4.2	4
4.5	3
4.6.1	4
4.6.2	2
4.7	2
4.8	1, 2
4.9	2
4.10	2

Chapter 5

Conclusion and future work

The proposed work consists in the development of a tool aiming at the selection of an optimal location for an insect-based industry. Such task has several possibilities as the concept of optimal location can be subjective and is affected by a number of possible conditionals and variables.

In this dissertation, the optimal location was defined as the location with the lowest overall costs. To achieve this, a mathematical model was developed that would estimate the overall costs of each potential location. This model took into consideration, transportation costs from suppliers and to customers, acquisition costs processing costs, and fixed plant costs. The proposed model was subsequently tested in several scenarios conceived to emulate real-life situations.

The model demonstrated its ability to quickly provide a solution across a range of diverse scenarios, showcasing its adaptability in different situations. There are a variety of factors that can be considered for the calculation such as the geographical locations of plants, suppliers, and customers, the type of vehicles used, the scale of operations, types of substrates with different conversion ratios, seasonality of subtract availability and cost, number of plants, among others that can be indirectly factored in the calculation of the model parameters. The test runs demonstrated how the previously referred factors influence the model and effectively alter (or not) its output.

As possible future research, there could be the incorporation in the model of a logistic redistribution center either for the substrate or for the final product. Additionally, expanding the scope of the model to include more potential locations and suppliers would allow for an evaluation of the model's run time as the problem instance increases. Furthermore, the model could be modified to incorporate non-financial inputs such as environmental impact or workforce culture, which could be weighted alongside total cost to determine the optimal location.

References

Aranaz, I., Acosta, N., Civera, C., Elorza, B., Mingo, J., Castro, C., Gandía, M. D. l. L., and Heras Caballero, A. (2018). Cosmetics and cosmeceutical applications of chitin, chitosan and their derivatives. *Polymers*, 10(2).

Ballou, R. H. (1973). Potential error in the center of gravity approach to facility location. *Transportation Journal*, 13(2):44–50.

Bava, L., Jucker, C., Gislon, G., Lupi, D., Savoldelli, S., Zucali, M., and Colombini, S. (2019). Rearing of *Hermetia illucens* on different organic by-products: Influence on growth, waste reduction, and environmental impact. *Animals*, 9.

Beesigamukama, D., Subramanian, S., and Tanga, C. M. (2022). Nutrient quality and maturity status of frass fertilizer from nine edible insects. *Scientific Reports*, 12.

Broeckx, L., Frooninckx, L., Slegers, L., Berrens, S., Noyens, I., Goossens, S., Verheyen, G., Wuyts, A., and Miert, S. V. (2021). Growth of black soldier fly larvae reared on organic side-streams. *Sustainability (Switzerland)*, 13.

Bulak, P., Proc, K., Pytlak, A., Puszka, A., Gawdzik, B., and Bieganowski, A. (2021). Biodegradation of different types of plastics by tenebrio molitor insect. *Polymers*, 13(20).

Carlo, H. J., Aldarondo, F., Saavedra, P. M., and Torres, S. N. (2012). Capacitated continuous facility location problem with unknown number of facilities. *Engineering Management Journal*, 24(3):24–31.

Carlo, H. J., David, V., and Salvat-Dávila, G. S. (2017). Transportation-location problem with unknown number of facilities. *Computers & Industrial Engineering*, 112:212–220.

Diener, S., Solano, N. M. S., Gutiérrez, F. R., Zurbrügg, C., and Tockner, K. (2011). Biological treatment of municipal organic waste using black soldier fly larvae. *Waste and Biomass Valorization*, 2:357–363.

Entogreen (n.d.). Entogreen.com. https://www.entogreen.com/timeline/a-primeira-fabrica-da-entogreen-entrara-em-laboracao-com-capacidade-para-a-biodigestao-de-3000-ton-de-sub-produtos-por-mes-e-uma-producao-estimada-de-2600-toneladas-de-proteina-500-toneladas-de-oleo/. Accessed: 5/2023.

Europa-Camioes.com (n.d). https://www.europa-camioes.com/. Accessed: 4/2023.

European Parliament, Council of the EU (2001). Commission regulation (eu) 999/2001. *Official Journal of the European Union*, 60:93–120.

European Parliament, Council of the EU (2009). Regulation (ec) no 767/2009. *Official Journal of the European Union*, 52:1–29.

European Parliament, Council of the EU (2011). Commission regulation (eu) 142/2011. *Official Journal of the European Union*, 54.

European Parliament, Council of the EU (2017). Commission regulation (eu) 2017/893. *Official Journal of the European Union*, 60:93–120.

European Parliament, Council of the EU (2021). Commission regulation (eu) 2021/1372. *Official Journal of the European Union*, 64.

IPFF (2022). *Guide on Good Hygiene and Practices for European Union producers of insects as food and feed*.

Jin, N., Liu, Y., Zhang, S., Sun, S., Wu, M., Dong, X., Tong, H., Xu, J., Zhou, H., Guan, S., and Xu, W. (2022). C/n-dependent element bioconversion efficiency and antimicrobial protein expression in food waste treatment by black soldier fly larvae. *International Journal of Molecular Sciences*, 23.

Kulka, K. and Sionkowska, A. (2023). Chitosan based materials in cosmetic applications: A review. *Molecules*, 28.

Liu, C., Yao, H., and Wang, C. (2021). Black soldier fly larvae can effectively degrade oxytetracycline bacterial residue by means of the gut bacterial community. *Frontiers in Microbiology*, 12.

Madau, F. A., Arru, B., Furesi, R., and Pulina, P. (2020). Insect farming for feed and food production from a circular business model perspective. *Sustainability*, 12(13).

Mannaa, M., Mansour, A., Park, I., Lee, D.-W., and Seo, Y.-S. (2024). Insect-based agri-food waste valorization: Agricultural applications and roles of insect gut microbiota. *Environmental Science and Ecotechnology*, 17.

Nunes, D. F. (2022). Ecosapo: Portuguesa entogreen abre laboratório de insetos em santarém. https://eco.sapo.pt/2022/06/01/portuguesa-entogreen-abre-laboratorio-de-insetos-em-santarem/#:~:text=A%20empresa%20portuguesa%20EntoGreen%20abriu,empregar%20cerca%20de%2060%20pessoas. Accessed: 5/2023.

Oonincx, D. G. A. B., van Itterbeeck, J., Heetkamp, M. J. W., van den Brand, H., van Loon, J. J. A., and van Huis, A. (2010). An exploration on greenhouse gas and ammonia production by insect species suitable for animal or human consumption. *PLoS ONE*, 5:e14445.

Poveda, J. (2021). Insect frass in the development of sustainable agriculture. a review. *Agronomy for sustainable development*, 41(1).

Qian, Y., Song, K., Hu, T., and Ying, T. (2018). Environmental status of livestock and poultry sectors in china under current transformation stage. *Science of The Total Environment*, 622-623:702–709.

Rehman, K. u., Hollah, C., Wiesotzki, K., Heinz, V., Aganovic, K., Rehman, R. u., Petrusan, J.-I., Zheng, L., Zhang, J., Sohail, S., Mansoor, M. K., Rumbos, C. I., Athanassiou, C., and Cai, M. (2023). Insect-derived chitin and chitosan: A still unexploited resource for the edible insect sector. *Sustainability*, 15(6).

Ritchie, H., Rosado, P., and Roser, M. (2022). Environmental impacts of food production. *Our World in Data*. https://ourworldindata.org/environmental-impacts-of-food. Accessed: 6/2023.

Smet, J., Wynants, E., Cos, P., and Van Campenhout, L. (2018). Microbial community dynamics during rearing of black soldier fly larvae (*Hermetia illucens*) and its impact on exploitation potential. *Applied and Environmental Microbiology*, 84.

Sridharan, R. (1995). The capacitated plant location problem. *European Journal of Operational Research*, 87(2):203–213.

Steinfeld, H., Gerber, P., Wassenaar, T. D., Castel, V., Rosales, M., Rosales, M., and de Haan, C. (2006). *Livestock's long shadow: environmental issues and options*. Food & Agriculture Org.

Suckling, J., Druckman, A., Small, R., Cecelja, F., and Bussemaker, M. (2021). Supply chain optimization and analysis of *Hermetia illucens* (black soldier fly) bioconversion of surplus foodstuffs. *Journal of Cleaner Production*, 321.

Tallentire, C., Mackenzie, S., and Kyriazakis, I. (2018). Can novel ingredients replace soybeans and reduce the environmental burdens of european livestock systems in the future? *Journal of Cleaner Production*, 187:338–347.

van Raamsdonk, L. W. D., van der Fels-Klerx, H. J., and de Jong, J. (2017). New feed ingredients: the insect opportunity. *Food Additives & Contaminants: Part A*, 34(8):1384–1397.

Volvotrucks (n.d). https://www.volvotrucks.com.pt. Accessed: 4/2023.

Yildirim-Aksoy, M., Eljack, R., Schrimsher, C., and Beck, B. H. (2020). Use of dietary frass from black soldier fly larvae, *Hermetia illucens*, in hybrid tilapia (nile x mozambique, oreocromis niloticus x o. mozambique) diets improves growth and resistance to bacterial diseases. *Aquaculture Reports*, 17.

Appendix A

Appendix A - Results of the model runs

In this appendix are presented the outputs of the model runs referred on chapter 4. Any variable not listed here has a value of 0.

4.2

Table A.1: x_{ijts}

i	j	t	s	x_{ijts}
1	1	1	1	12 500
2	1	1	1	12 500
3	1	1	1	12 500
4	1	1	1	2 500

Table A.2: y_j

j	y_j
1	1
2	0
3	0
4	0

Table A.3: z_{jk}

j	k	z_{jk}
1	1	3000

4.3

Table A.4: x_{ijts}

i	j	t	s	x_{ijts}
1	4	1	1	2 500
2	4	1	1	12 500
3	4	1	1	12 500
4	4	1	1	12 500

Table A.5: y_j

j	y_j
1	0
2	0
3	0
4	1

Table A.6: z_{jk}

j	k	z_{jk}
4	1	3000

4.4
4.4.1

Table A.7: x_{ijts}

i	j	t	s	x_{ijts}
1	4	1	1	0
2	4	1	2	9 375
3	4	1	3	12 500
4	4	1	4	12 500

Table A.8: y_j

j	y_j
1	0
2	0
3	0
4	1

Table A.9: z_{jk}

j	k	z_{jk}
4	1	3000

4.4.2

Table A.10: x_{ijts}

i	j	t	s	x_{ijts}
1	4	1	1	0
2	4	1	2	9 375
3	4	1	3	12 500
4	4	1	4	12 500

Table A.11: y_j

j	y_j
1	0
2	0
3	0
4	1

Table A.12: z_{jk}

j	k	z_{jk}
4	1	3000

4.5

Table A.13: x_{ijts}

i	j	t	s	x_{ijts}
1	3	1	1	12 500
2	3	1	1	12 500
3	3	1	1	2 500
4	3	1	1	12 500

Table A.14: y_j

j	y_j
1	0
2	0
3	1
4	0

Table A.15: z_{jk}

j	k	z_{jk}
3	1	3000

4.6
4.6.1

Table A.16: x_{ijts}

i	j	t	s	x_{ijts}
1	4	1	1	12 500
2	4	1	1	2 500
3	4	1	1	12 500
4	4	1	1	12 500

Table A.17: y_j

j	y_j
1	0
2	0
3	0
4	1

Table A.18: z_{jk}

j	k	z_{jk}
4	1	100
4	2	2 000
4	3	300
4	4	600

4.6.2

Table A.19: x_{ijts}

i	j	t	s	x_{ijts}
1	2	1	1	12 500
2	2	1	1	2 500
3	2	1	1	12 500
4	2	1	1	12 500

Table A.20: y_j

j	y_j
1	0
2	1
3	0
4	0

Table A.21: z_{jk}

j	k	z_{jk}
2	1	100
2	2	2 000
2	3	300
2	4	600

Table A.22: h_{jl}

j	l	h_{jl}
2	1	10 000
2	3	10 000
2	4	10 000

4.7

Table A.23: x_{ijts}

i	j	t	s	x_{ijts}
1	2	1	1	6 250
2	2	1	1	1 250
3	2	1	1	6 250
3	2	2	1	7 000
4	2	1	1	6 250
4	2	2	1	13 000

Table A.24: y_j

j	y_j
1	0
2	1
3	0
4	0

Table A.25: z_{jk}

j	k	z_{jk}
2	1	100
2	2	2 000
2	3	300
2	4	600

4.8

Table A.26: x_{ijts}

i	j	t	s	x_{ijts}
1	1	1	1	12 500
2	1	1	1	7 500
3	2	1	1	7 500
4	2	1	1	12 500

Table A.27: y_j

j	y_j
1	1
2	1
3	0
4	0

Table A.28: z_{jk}

j	k	z_{jk}
2	1	100
2	2	2 000
2	3	300
2	4	600

4.9

Table A.29: x_{ijts}

i	j	t	s	x_{ijts}
2	2	1	2	4 687
3	2	1	3	6 250
3	2	2	3	8 000
4	2	1	4	6 250
4	2	2	4	7 333

Table A.30: y_j

j	y_j
1	0
2	1
3	0
4	0

Table A.31: z_{jk}

j	k	z_{jk}
2	1	100
2	2	2 000
2	3	300
2	4	600

Table A.32: h_{jl}

j	l	h_{jl}
2	1	10 000
2	3	2 521
2	4	10 000

4.10

Table A.33: x_{ijts}

i	j	t	s	x_{ijts}
2	2	1	2	4 687
3	2	1	3	6 250
3	2	2	3	8 000
4	2	1	4	6 250
4	2	2	4	7 333

Table A.34: y_j

j	y_j
1	0
2	1
3	0
4	0

Table A.35: z_{jk}

j	k	z_{jk}
2	1	100
2	2	2 000
2	3	300
2	4	600

Table A.36: h_{jl}

j	l	h_{jl}
2	1	10 000
2	3	2 521
2	4	10 000