Extended Abstract to obtain the Master of Science Degree in
Industrial Engineering and Management

Design and Planning of the Logistics System associated with an Innovative Glass Packaging Recovery System

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Abstract: Urban waste is a very complex and relevant problem in recent years due to the harmful impacts it can cause on the environment and human health. The imposition of ambitious recycling targets by the European Union has led several countries, including Portugal, to seek alternatives to the recovery of this waste. Therefore, Sociedade Ponto Verde has launched an initiative in which it will resort to the investment of a selective number of innovative projects in the development of a circular economy. The present work is part of this initiative, and the objective is to rescue glass from landfill operations by carrying out a logistical planning associated with a system with diagrams capable of recovering this material from municipal solid waste. A mixed logistic system will be explored, characterized by mobile and fixed glass recovery units, leveraging its financial viability. Two models have been developed for this purpose: the first is a stochastic model of location and sizing that considers the change in the composition of the product to be processed in terms of the presence of glass along the time horizon, in which investment decisions in the system are determined; the second is a routing model that uses the outputs of the first model to sequence the visits of the mobile units and determine the costs associated with these travels. The results of the model developed in GAMS concluded that a fixed approach will be the most beneficial considering all the scenarios involved.

Keywords: Waste Management, Network Design, Routing Problems, Location Problems, Demand Uncertainty

1. Introduction

The production of waste is directly associated with human activity, so an adequate management of its flows is necessary for the implementation of a new growth paradigm, thus respecting the limits of the planet (REA, 2019). Urban waste and its management have different characteristics that distinguish them from other waste streams, representing a high and diffuse number of producers. Although this waste represents only 10% of the total waste generated in Europe, it is one of the most polluting categories of waste and the category with the greatest potential for environmental improvement through better management (European Commission, 2016). Developing regulations and investing in waste treatment infrastructure such as landfills, waste incineration plants and waste sorting and recovery facilities are some of the behaviours of European countries to manage their waste in a reliable and environmentally sound manner. However, these initiatives are proving to be insufficient, as there are still relatively high values of waste that is disposed of without any prior treatment (EEA, 2015). Ponto Verde Innovation, an initiative of Sociedade Ponto Verde (SPV), follows the promotion of bases such as sustainable growth and circular economy, financing a selective set of innovative projects, in which Mobile-Pro-U, presented by IST-ID – Instituto Superior Técnico Association for Research and Development - was chosen. Given that about 50% of the glass is being landfilled, it is necessary to find ways to recover it effectively. The purpose of this project is to increase the value of glass recycling through the design and planning of a logistic system that includes innovative glass recovery diagrams. These have a chance to be embedded in mobile units (called Mobile-Pro-U) that are transported to Biological-Mechanical Treatment plants (also designated in this work as TMBs). These TMBs process municipal solid waste and their main objective is that, at the end of the process, recyclable materials (which are forwarded for recycling), organic materials (which are forwarded to the production of compost) and rejected materials (which are usually landfilled) are separated and obtained. The latter is divided by a flow of light rejects - based on fine plastics and paper - and a flow of heavy rejects (designated by TMBr in this work), which, given the inefficiency of the processes suffered for its separation, has a strong presence of glass. Thus, heavy rejects of undifferentiated waste (TMBr) are the product where the potential recovery can be obtained. The diagrams include a technology developed by CERENA (Natural Resources and Environment Center of the Instituto Superior Técnico), called RecGlass, which allows the obtaining of this resource in an efficient way.

The objective of the present study is to leverage the financial viability of these diagrams by studying a mixed logistic system associated with the implementation of two types of equipment: fixed diagrams, which are installed next to the TMBs, and mobile units, which are capable of processing in different locations. A mathematical model is to be developed to aid in the finding of the best possible configuration for the logistics system. The model will also take into consideration the possible scenarios of the percentage of glass present in the rejects of these facilities, which is forecasted to reduce in the upcoming years due to new initiatives to reduce this type of waste stream. Since this is an investment, the models will consider that the goal is to maximize the Net Present Value (NPV).

The paper is structured as follows: in Section 2, relevant literature on location, routing, location routing and stochastic problems is presented. In Section 3, the problem statement is identified. The mathematical models are presented in Section 4. In Section 5 the results of each system are shown. A sensitivity analysis is conducted to study the influence of the variation of certain parameters, in section 6. Finally, in section 7 conclusions are drawn.

2. Literature review

2.1. Location Problems

One of the major logistical challenges in a supply chain is related to the design of the distribution network, in which the number, location, size of the necessary facilities, assignment of points of sale to the warehouses and main supply decisions are determined (Simchi-Levi et al, 2007). These decisions of the physical configuration of the supply chain have a strategic character, since it is considered that the high costs associated with the acquisition of properties and construction of facilities, turn localization projects into long-term programs, since this is usually the only way they can become profitable (Owen, S. H. & Daskin, 1998). The literature on localization problems is extensive due to the high complexity and different particularities of each company and is therefore studied and applied in several cases. Facility Location Problem (FLP) models involve a set of customers and a set of possible locations for the facilities that will serve the customer. The challenge is to decide where to place the facilities and how to allocate customers and their demand to the facilities in operation (Owen & Daskin, 1998). Regarding the topic of waste management, a real case studied by Rathore and Sarmah (2019) stands out, in which a Facility Location Problem was proposed using a Mixed Integer Linear Programming (MILP) model to find the optimal location for the waste transfer stations, considering their economic viability. For this purpose, a geographic information system was used to store inputs necessary for the model. The problem has different scenarios, considering waste separation by the final consumer and the creation of a logistic planning assuming that each type of waste will be forwarded to specific transfer stations, or not considering waste separation, and consequently, in this case, the transfer stations receive all types of waste. These scenarios have repercussions in terms of the products that are received, their quantity and their frequency. Directly linked to the present project, one can refer to the model of location and sizing for the study of a fixed point system regarding the recovery of glass developed by Castel-branc (2019), in which the objective was based on the maximization of the NPV, and in which the number of fixed installations to be opened and their location, the number of diagrams necessary in each installation, the heavy reject flows to other TMBs and to landfill and the amount of recovered glass were determined.

2.2 Vehicle Routing Problems

The Vehicle Routing Problem (VRP) consists in finding the routes that allow a set of vehicles (with one or several initial locations) to reach a number of geographically dispersed points. The routes must completely satisfy the search needs of the entities of that route, which starts and ends at the same point. Generally, these problems have as their main objective the minimization of the total costs of the routes, the sum of fixed and variable costs, the total distance travelled, the number of vehicles used or even the environmental impacts. Within the universe of VRP, the most studied and most likely adapted to the context of the problem are the following (Braekers et al., 2016; Toth & Vigo, 2002): Capacitated VRP (CVRP): In the CVRP the vehicle has a previously determined capacity, which will have to be equal or higher than the total demand of the customers served by that vehicle (Baldacci et al., 2010). It is possible to extend this problem by varying the capacities, which results in the so-called Heterogeneous Fleet VRP (HFVRP) or Mixed Fleet VRP (MFVRP); VRP with Time Windows (VRPTW): This aspect assumes that deliveries to a given customer must occur in an established time interval. If the vehicle arrives at the location before the beginning of the time interval, it will have to wait until it reaches it and only then it can perform its job. The objective is to minimize the number of vehicles needed and the distances or travel times, and this is a problem often used in waste collection problems (Cordeau, J. F., et al 2000). Regarding solely on the topic of waste collection, one can highlight the work of Ramos et al. (2018), in which a Smart Waste Collection Routing Problem was studied, whose objective is to reduce the uncertainty associated with the ideal moment to collect waste containers. In this way, the collection becomes more efficient, maximizing the collected garbage and minimizing the transport cost. The work includes three different approaches, the first being a limited approach, based on a heuristic First-Route Second Cluster, where a minimum filling level rate is stipulated, which is coupled with a CVRP that aims to maximize the amount of waste collected, minimizing the distance travelled. The other two are Smart Collection approaches: the first through a mathematical model that decides which containers to visit and optimizes the sequence to carry out, to maximize profit; and the second through a heuristic method in which the days of collection are obtained according to the established level of service, so that the previously defined mathematical model is then applied. Markov, I., Varone, S., & Bierlaire, M. (2016) also carried out a work related to waste collection, where they proposed the resolution of a VRP integrating a heterogeneous fixed fleet and a flexible assignment of destination deposits. Several restrictions are also included, such as mandatory break times (which depend on the time the trip starts), vehicle capacities and limitations of each location. The problem is defined as a MILP (Mixed-Integer Linear Programming), and given the complex nature of the problem, its application is only valid in small to medium sized cases. To solve more realistic cases, a multiple neighbourhood search heuristic is proposed, capable of including all the characteristics of the problems and their restrictions.

2.3 Dealing with Uncertainty in Location Problems

In its classical form, location problems (FLP) are static and deterministic, where all information is known precisely and is available before the problem resolution begins. However, by nature, these are optimization problems that deal with future events in an environment that usually includes significant sources of uncertainty. When the time horizon of the project is considerably high (as is the case with the project in hand), it can be expected that there will be increased uncertainty in some of the parameters of the model. The inclusion of such unpredictability in the model allows for a more correct analysis of possible scenarios and a greater degree of confidence in the values obtained (Oyola, J., 2018). One example of the inclusion of uncertainty in location models is demonstrated in the work of Yu, H. et al (2020), who proposed a bi-objective stochastic linear program (MILP) to support decisions related to hazardous waste management in order to reduce the population's exposure to risk while maintaining cost efficiency in the transportation and treatment of hazardous waste. To this end, the uncertainty inherent in the planning horizon - cost, demand and affected population - are defined as stochastic parameters. To solve the mathematical model, a programming approach based on a mean approximation sample (SAA-GP) is used. The proposed model and solution method are validated through numerical experiments whose results show that uncertainty can not only affect the value of the objective function but also lead to different strategic decisions in the design of a hazardous waste management system network. The model is also applied in a real study of health care waste management in Wuhan, China, to show its applicability. Popela, P. et al (2017) also developed a location problem regarding waste treatment facilities, where a stochastic programming approach was used. This model allows the establishment of a set of optimal operational waste treatment units in relation to the total expected cost, which includes processing, transportation and investment costs. The modelling of the location problem is done by considering random and variable production of waste, obtained through a stochastic linear program, based on scenarios. The model also evaluates the behaviour of the waste producers based on the assumption that they are environmentally friendly. The modelling ideas are illustrated in a limited size example solved in GAMS, and computations in larger instances were performed with traditional and heuristic algorithms, implemented within MATLAB.

3. Problem Statement

As mentioned in chapter one, this project aims to increase the amount of glass recycled in Portugal, by using diagrams exclusively made for this purpose. The problem is that that the equipment needed requires a financial investment that the interested entities – in which the Biological-Mechanical Treatment plants (TMBs) are included - were not able to endure, due to the lack of financial return. To prove that this system can be financially viable, an extensive research work regarding the legal, economic, social and logistical context of this project was done. For this purpose, the support of all entities involved, especially TMBs, was crucial in terms of data collection and context awareness, so that the model could be developed. The existent work regarding this project was also mentioned, since it contemplates a lot of the data used as input in the model. The mixed logistic system developed should be able to make decisions on what TMBs to work with to assure the recuperation of the glass with maximum profit. This system is characterized by the implementation of fixed diagrams – in which the equipment is solely used in the location of a TMB, with the particularity of being able to transport rejected waste of other TMBs to its own – and mobile units with glass recovery diagrams installed in them. The goal is to allocate the fixed equipment to TMBs where there is a big amount of waste to process, while the mobile units could work in several TMBs that would require less time to process.

4. Approach Explanation

The existence of a mobile component in the model implies that only one location model is insufficient for the optimal system characterization, since it lacks information regarding the sequence of visits of the mobile units and the value of the transport costs associated with these displacements, which end up being characteristics of routing models. The solution proposed in this work divides the study of the logistic system into two interlinked parts: a stochastic location and sizing model, in which the investment decisions in the diagrams of different typologies and the processing locations will be defined, while assuring the maximization of the Net Present Value (NPV); and a routing model which, by introducing outputs from the location model, will define the optimal routes to be carried out by the mobile units, with the objective of minimizing transportation costs. One of the criticisms to this phased analysis is the lack of consideration of the transportation costs of the mobile units in the investment decisions, since these can have an impact on the final solution, because, if ignored, it can lead to a non-optimal decision making. In order to understand the influence of these travel costs on the model decisions, a Worst Case Scenario Analysis was made in which it is intended to simulate a rather pessimistic scenario of the transport cost value of mobile diagrams. The results showed that these costs have a rather insignificant value when compared with other operational costs necessary to assure the good functionality of the logistic system and its components.

Stochastic Location and Dimensioning Model

The developed model intends to determine the number of fixed and/or mobile diagrams (and their typology) to be used and define in which locations they should work to maximize the Net Present Value (NPV). This is a stochastic model, since to combat the uncertainty associated with the percentage of glass present in the heavy reject $Vp_{a,s}$, a set of pre-defined scenarios will be included, which will have a probability of event Pr_s associated to each one of them. The optimal solution will be the one that reaches a higher expected NPV value, using the same combination of fixed and mobile diagrams by the different scenarios. The NPV achieved includes the gains from the sale of the glass obtained and the landfill space rescued due to the processing of the reject; and retains costs associated with the investment in diagrams, operating costs, human resources and transportation costs related to the displacement of reject between fixed installations (that are distinct from the transportation costs of mobile units, which are not included in this model), which work in a centralized manner, that is, allowing the product processing of distinct installations in a centralized facility. The activities occur in processing locations j, which are located next to the TMBs. Therefore, each process location j has a TMB i associated with it. It is also important to mention that the model divides the time periods in two forms: periods a, where the formulation is considered on a yearly manner; and periods t, which are time intervals in which the year is divided, and they define the minimum time that a mobile unit can be processing in a certain TMB.

Mathematical Formulation

Sets

I	Set of TMB locations i ∈ I
J	Set of processing locations j ∈ J
T	Set of time periods t ∈ T
A	Set of annual periods to ∈ A
K	Set of diagram typologies k ∈ K
S	Set of scenarios s ∈ S

Indexes

i	Entity TMB - i = e1,...I
j	Entity Location Processing - j = c1,....J
t	Entity Time period t - t = 1...,Tmax , t = {a(t),b(t)}
a	Entity annual time period - a = a1, a2,...Amáx
k	Entity Diagram- k= k1,...,K, k = {f(k),m(k)}
s	Entity Scenario - s= s1,..., S

Binary variables

$Y_{j,k}$ Existence or not of fixed diagrams in j during the time horizon;

$Ya_{j,k,a,s}$ Fixed installation running in j, in year a and scenario s;

Discrete variables and not negative variables

$NDf_{j,k}$ Number of fixed diagrams to invest in installation j

$NDfa_{j,k,a,s}$ Number of fixed diagrams in operation in j, in year a and scenario s

$NDfm_{j,k,t,s}$ Number of fixed diagrams in operation in j, in period t and scenario s

$NDgm_k$ Number of k type mobile diagrams to invest in the system

$NDma_{k,a,s}$ Number of k type mobile diagrams in operation in year a and scenario s

$NDm_{j,k,t,s}$ Number of k-type mobile diagrams in operation in installation j, in period t and scenario s

$FNDma_{j,k,a,s}$ Fraction of the number of mobile diagrams type k existing in j, in year a and period s

H_j Maximum number of mobile diagrams in a given period t in installation j, over the time horizon

Continuous variables and not negative

$Qm_{i,j,k,t,s}$ Amount of reject (TMBr), in tons, processed by the k-diagram, from the TMB i and shifted to the processing installation j, in period t and scenario s (input flow into the installation)

$Qa_{i,j,k,a,s}$ Amount of TMBr (in ton) processed by the k-diagram, coming from the TMB i and moved to the processing facility j, in year a and scenario s (input flow into the facility)

$QDm_{j,i,k,t,s}$ Amount of TMBr processed by k-diagram, which does not contain glass, from the processing facility j and moved to TMB i, in period t and scenario s (output flow)

$QDa_{j,i,k,a,s}$ Amount of TMBr processed by k-diagram, which does not contain glass, from the processing facility j and moved to TMB i, in year a and scenario s (output flow)

$TMBr_{i,t,s}$ Quantity of TMBr for processing in i, in period t and scenario s

Auxiliary variables in the objective function

CI Initial investment cost

CL Investment in fixed installations and support equipment

CD Investment in the diagrams

CDu_j Investment in fixed diagrams in the processing facility j

$CHu_{a,s}$ Human resources cost in year a and scenario s

$Ce_{a,s}$ Electricity costs in year a and scenario s

$Cm_{a,s}$ Costs of maintenance of all diagrams in year a, in scenario s

$CTr_{a,s}$ Transport costs associated with TMBr movements between TMB stations for use in fixed diagrams, in year a, in scenario s

$P_{i,j,k,a,s}$ Quantity of final product to sell (glass, in tons) of TMB i, processed at installation j, in year a and scenario s

$CF_{a,s}$ Cash Flow in year a and scenario s

$Res_{a,s}$ EBIT in the year a and scenario s

$RL_{a,s}$ Net Income in year a and scenario s

DC_a Capital Depreciation in year a

Parameters

Installation, Diagram and Mobile Units

CLu Cost of investment in a land to use the fixed diagrams

Arm Investment cost in a processing plant to use the fixed diagrams

CEq Cost of support equipment for the diagrams

E Effectiveness of diagrams in glass recovery

Cap_k Processing capacity for each period t in the k−type diagram

U Rate of utilization of the diagrams

CDg_k Typology diagram cost k

Operational

$d_{i,j}$ Distance between i and j, in km

$Ckmt$ Cost per ton, per km, in euros

Cw Annual cost per worker

N Number of 8 hour shifts to be operated per day

Cel Cost of electricity per ton

Cmt_k Maintenance cost for each k-type diagram and per period t

Ai Cost of internal landfill per ton

Aex External landfill cost per ton

Product

V_i Percentage of glass present in the heavy reject in i

$Vp_{a,s}$ Percentage of glass present in TMBr in year a and scenario s

Pu Price or return value per ton of final product, in EUR

RP_i Quantity of TMBr produced annually in i

α_i Percentage of TMBr in i in the optimal particle size range to process

Financial

$Ti_{a,s}$ Interest rate in year a and scenario s

Ta Discount rate

Outros

Pr_s Probability of scenario s to be verified

MA No. of t periods t in each year a

Objective function

Equation 1: Maximization of Net Present Value (defined as VAL)

$$Max\ VAL = \sum_{a\in A}\sum_{s\in S}\left(Pr_s * \frac{CF_{a,s}}{(1+Ta)^a}\right) - CI \tag*{[1]}$$

Auxiliary equations

Equation 2: Cash Flow per year a and scenario s

$$CF_{a,s} = RL_{a,s} + DC_a \qquad ,\forall a \in A\backslash\{Amáx\} \tag*{[2(a)]}$$

$$CF_{a,s} = RL_{a,s} + DC_a + \sum_{j\in J}\sum_{k\in K} CLu * Y_{j,k} \qquad ,\forall a = Amáx \tag*{[2(b)]}$$

Equation 3: Annual EBIT per scenario s

$$\begin{aligned} Res_{a,s} = \Bigg[\Bigg(& Pu * \sum_{i\in I}\sum_{j\in J}\sum_{k\in K} P_{i,j,k,\mathrm{a},s} \\ &+ \sum_{i\in I}\sum_{j\in J}\sum_{k\in K}\left(Qa_{i,j,k,\mathrm{a},s} * Ai\right) \\ &- \sum_{j\in J}\sum_{i\in I}\sum_{k\in K}\left(QDa_{j,i,k,a,s} * Aex\right)\Bigg) \\ &- \left(Ce_{a,s} + CH_{a,s} + CTr_{a,s} + Cmu_{a,s} \right. \\ &\left. + DC_a\right)\Bigg] \end{aligned} \tag*{[3]}$$

Equation 4: Net annual results per scenario s

$$RL_{a,s} = \left(1 - Ti_{a,s}\right) * Res_{a,s} \tag*{[4]}$$

Equation 5: Annual depreciation of capital invested

$$DC_a = \frac{\left(CI - \sum_{j\in J}\sum_{k\in K} CLu * Y_{j,k}\ \right)}{Amáx} \tag*{[5]}$$

Equation 6: Calculation of initial investments

$$CI = CL + CD \tag*{[6]}$$

Equation 7: Location and Support Equipment Costs

$$CL = \sum_{j\in J}\sum_{k\in f(k)}(CLu + Arm + CEq) * Y_{j,k}\ + \sum_{j\in J}(CEq * H_j) \tag*{[7]}$$

Equation 8: Cost of all Diagrams

$$CD = \sum_{j\in J} CDu_j + \sum_{k\in K}(CDg_k * NDgm_k) \tag*{[8]}$$

Equation 9: Costs of fixed diagrams in entity j

$$CDu_j = \sum_{k\in K}\left[\left(\frac{CDg_k}{2}\right) * Y_{j,k} + \left(\frac{CDg_k}{2}\right) * NDf_{j,k}\right] \tag*{[9]}$$

Equation 10: Annual electricity cost per scenario s

$$Ce_{a,s} = Cel * \sum_{i\in I}\sum_{k\in K}\sum_{s\in S} Qa_{i,j,k,a,s} \tag*{[10]}$$

Equation 11: Annual maintenance costs per scenario s

$$Cmu_{a,s} = Cmt_k * \left(\left(\frac{Ya_{j,k,a,s}}{2}\right) + \left(\frac{NDfa_{j,k,a,s}}{2}\right) + NDm_{k,a,s}\right) \tag*{[11]}$$

Equation 12: Annual human resources costs per scenario s

$$CHu_{a,s} = Cw * N * \left(\sum_{j\in J}\sum_{k\in K} Ya_{j,k,a,s} + \sum_{k\in K} NDma_{k,a,s}\right) \tag*{[12]}$$

Equation 13: Transport costs of heavy rejects (TMBr) per year and scenario

$$CTr_{a,s} = Ckmt * \left(\sum_{i\in I}\sum_{j\in J}\sum_{k\in K} Qa_{i,j,k,a,s} * d_{i,j} + \sum_{i\in I}\sum_{j\in J}\sum_{k\in K} QDa_{j,i,k,a,s} * d_{j,i}\right) \tag*{[13]}$$

Equation 14: Amount of TMBr in entity i, in period t and scenario s

$$TMBr_{i,t,s} = RP_i - \sum_{j\in J}\sum_{k\in K} Qm_{i,j,k,t,s} \qquad ,\forall t \in a(t) \tag*{[14(a)]}$$

$$TMBr_{i,t,sc} = TMBr_{i,t-1,s} - \sum_{j\in J}\sum_{k\in K} Qm_{i,j,k,t,s} \qquad ,\forall t \in b(t) \tag*{[14(b)]}$$

Equation 15: Quantity of final product obtained in each year a and scenario s

$$P_{i,j,k,a,s} = Qa_{i,j,k,a,s} * V_i * Vp_{a,s} * E * U\ * \alpha_i \tag*{[15]}$$

Equation 16: Material balance from entity i, to entity j, with technology k, per year a and scenario s

$$QDa_{j,i,k,a,s} = Qa_{i,j,k,a,s} - P_{i,j,k,a,s} \tag*{[16]}$$

Equation 17: Material balance in each entity j, with technology k, per year a and scenario s

$$\sum_{i\in I} QDa_{j,i,k,a,s} = \sum_{i\in I}\left(Qa_{i,j,k,a,s} - P_{i,j,k,a,s}\right) \tag*{[17]}$$

Equation 18: Material balance per year a and scenario s

$$\sum_{j\in J}\sum_{i\in I}\sum_{k\in K} QDa_{j,i,k,a,s} = \sum_{i\in I}\sum_{j\in J}\sum_{k\in K}\left(Qa_{i,j,k,a,s} - P_{i,j,k,a,s}\right) \tag*{[18]}$$

Equation 19: TMBr processing in each entity i, by period t and scenario s

$$\begin{aligned} &\sum_{j\in J}\sum_{k\in K} Qm_{i,j,k,t,s} \le TMBr_{i,t,s} + RP_i \qquad ,\forall i \in I, \forall t \in a(t), \forall s \in S \\ &\sum_{j\in J}\sum_{k\in K} Qm_{i,j,k,t,s} \le TMBr_{i,t,s} \qquad ,\forall i \in I, \forall t \in b(t), \forall s \in S \end{aligned} \tag*{[19]}$$

Equation 20: Capacity restriction in each entity j, with technology k, by period t and scenario s

$$Cap_k * N * (NDfm_{j,k,t,s} + NDm_{j,k,t,s}) \ge \sum_{i\in I} Qm_{i,j,k,t,s} \quad ,\forall j \in J, \forall k \in K, \forall t \in T, \forall s \in S \tag*{[20]}$$

Equation 21: Annual capacity restriction in each j entity, with k technology and scenario s

$$Cap_k * N * MA *\ (NDfa_{j,k,a,s} + FNDma_{j,k,a,s}) \ge \sum_{i\in I} Qa_{i,j,k,a,s} \quad ,\forall j \in J, \forall k \in K, \forall a \in A, \forall s \in S \tag*{[21]}$$

Equation 22: Number of rejects processed annually per scenario s

$$Qa_{i,j,k,a,s} = \sum_{t\in an(t)} Qm_{i,j,k,t,s} \tag*{[22]}$$

Equation 23: Fraction of mobile diagrams type k in installation j in year a and scenario s

$$FNDma_{j,k,a,s} = \frac{\sum_{t \in an(t)} NDm_{j,k,t}}{MA} \qquad [23]$$

Equation 24: Number of mobile type k diagrams in the system during year a and scenario s

$$NDma_{k,a,s} \geq \sum_{j \in J} FNDma_{j,k,a,s} \quad ,\forall k \in K, \forall a \in A, \forall s \in S \qquad [24]$$

Equation 25: Number of fixed diagrams in operation during year a and scenario s

$$NDfa_{j,k,a,s} \geq NDfm_{j,k,t,s} \quad ,\forall j \in J, \forall k \in K, \forall t \in an(t), \forall a \in A, \forall s \in S \qquad [25]$$

Equation 26: Restriction of the number of mobile diagrams to act in the system in each period t and scenario s

$$\sum_{j \in J} NDm_{j,k,t,s} \leq NDgm_k \quad ,\forall k \in K, \forall t \in T, \forall s \in S \qquad [26]$$

Equation 27: Restriction of the number of mobile diagrams to act in the system in each year a and scenario s

$$NDma_{k,a,s} \leq NDgm_k \quad ,\forall k \in K, \forall a \in A, \forall s \in S \qquad [27]$$

Equation 28: Restriction of the number of diagrams in each installation j in each period t and scenario s

$$NDm_{j,k,t,s} \leq NDgm_k \quad ,\forall k \in K, \forall t \in T, \forall s \in S \qquad [28]$$

Equation 29: Restriction of the number of fixed diagrams in each period t and scenario s

$$NDfm_{j,k,t,s} \leq NDf_{j,k} \quad ,\forall j \in J, \forall k \in K, \forall t \in T, \forall s \in S \qquad [29]$$

Equation 30: Restriction of the number of fixed diagrams in each year a and scenario s

$$NDfa_{j,k,a,s} \leq NDf_{j,k} \quad ,\forall j \in J, \forall k \in K, \forall a \in A, \forall s \in S \qquad [30]$$

Equation 31: Relation between the number of fixed diagrams and fixed installations in j

$$NDf_{j,k} \geq Y_{j,k} \quad ,\forall j \in J, \forall k \in K \qquad [31]$$

Equation 32: Relation between the number of fixed diagrams and fixed installations in j in year a

$$NDfa_{j,k,a,s} \geq Ya_{j,k,a,s} \quad ,\forall j \in J, \forall k \in K, \forall a \in A, \forall s \in S \qquad [32]$$

Equation 33: Maximum number of moving diagrams associated with each j installation in a given period

$$H_j \geq \sum_{k \in K} NDm_{j,k,t,s} \quad ,\forall j \in J, \forall t \in T, \forall s \in S \qquad [33]$$

Equation 34: Existence of flow from fixed typologies in TMB station each year a

$$Qa_{i,j,k,a,s} \leq BigM * Ya_{j,k,a,s} \quad ,\forall i \in I, \forall j \in J, \forall k \in f(k), \forall a \in A, \forall s \in S \qquad [34]$$

Equation 35: Existence of flow from mobile typologies in TMB station in each period t

$$Qm_{i,j,k,t,s} \leq BigM * NDm_{j,k,t,s} \quad ,\forall i \in I, \forall j \in J, \forall k \in m(k), \forall t \in T, \forall s \in S \qquad [35]$$

Equation 36: Relation between the fixed installations in operation at a and the existence of the fixed installation

$$Ya_{j,k,a,s} \leq Y_{j,k} \quad ,\forall j \in J, \forall k \in K, \forall a \in A, \forall s \in S \qquad [36]$$

Equation 37: Number of rejects processed with mobile diagrams with entities i different from entities j

$$\sum_{k \in m(k)} Q_{i,j,k,t,s} = 0 \quad ,\forall i,j \neq IJ \quad ,\forall k \in f(k), \forall t \in T, \forall s \in S \qquad [37]$$

Equation 38: Obligation of investment in the system

$$\sum_{j \in J} \sum_{k \in K} Y_{j,k} + \sum_{k \in K} NDgm_k \geq 1 \qquad [38]$$

Equation 39: Restriction of the number of fixed diagrams of mobile typology

$$\sum_{k \in m(k)} NDf_{j,k} = 0 \quad ,\forall j \in J \qquad [39]$$

Equation 40: Restriction of the number of mobile diagrams to be invested of fixed typology

$$\sum_{k \in f(k)} NDgm_k = 0 \qquad [40]$$

The objective function in equation [1], intends to maximize the net present value (defined as VAL) of the system during the time horizon of the project. The discounted Cash Flows of the years of analysis are added and multiplied by the probability of event of each scenario, from which the initial investment cost of the project is subtracted. The Free Cash Flow calculation results from the addition of the capital depreciation to the Net Results. For the last year, the residual value of the investment in the project is added (which in this case is the cost of the land necessary to build a processing plant). The calculation of the annual EBIT is represented in equation [3]. Here all revenue sources and all variable costs of the system are considered. The revenues are determined by the return value of the recovered glass and by the gain referring to the space released in the landfill by that same recovery. The operating costs and depreciation are then subtracted to this amount. The net results for each year [4] are calculated through the multiplication of the interest rate with the EBIT. The annual depreciation of capital is given through the use of the straight-line method, also used in (Cardoso et al, 2013) where it is assumed that during the useful life of the invested assets, these have an associated cost that will be equal to their division into equal parts during the period considered. The initial investment cost of the project [6] includes the cost of process locations, and support equipment [7] and the cost of all diagrams [8]. The costs of fixed diagrams in each entity j [9] have a scale factor. Equations [10] to [13] represent the operational costs of the system. The calculation of the amount of reject in each installation i [14] results from the TMBr to process in the previous period minus the quantity processed in the given period (a(t) – beginning of the year; b(t) – remaining periods). The amount of glass annually obtained [15] is obtained through the annual processing of TMBr. Its value depends on the percentage of glass in each installation, the percentage of glass in the heavy reject in each year a and in each scenario s, the usage rate, the efficiency of the diagrams and the percentage of TMBr in each installation i that is within the particle size needed to process. Equations [16] to [18] establish the relation between the input flow of TMBr to be processed with the output flow for landfill and the recovered glass flow. Equations [19] demonstrate the TMBr processing restriction, which is associated with the amount of reject that is in TMB i in a given period t. Equation [20] and [21] represent capacity constraints during each period t and year a. Equation [22] calculates the annual processed quantity in each installation j. The fraction of mobile diagrams of each type in processing locations j and in each year a is given in equation [23]. The number of mobile diagrams k acting in each year [24] is an integer variable that is characterized by having a value greater than or equal to the sum of fractions of movable diagrams in all j installations. Equations [26] to [32] and the equation [36] establish the relation between the decision variables $Y_{j,k}$, $NDf_{j,k}$and $NDgm_k$ with the variables that vary with each scenario s. The restriction [33] calculates the maximum number of mobile diagrams present in each installation j in the same time period t. Equations [34] and [35] establish that there will only be processing of the reject at location j for the respective fixed (f(k)) and mobile (m(k)) typologies, if in fact there is a fixed installation in operation in the year a or a mobile diagram in the period t. Equation [37] requires that the mobile diagrams process only the TMBr coming from a TMB i associated to an entity j with the same location. That is, only the processing of the set IJ is allowed, which concerns the pair of installations i and j with the same number (for example i1 and j1, i10 and j10). The restriction [38] requires that at least one fixed or mobile diagram must be implemented. Finally, equations [39] to [40] ensure that the fixed and mobile diagrams are strictly associated with their groups *f(k)* and *m(k)* respectively.

Two-Commodity flow CVRP Model

The routing model developed aims at minimizing the transportation costs associated with travel between TMBs in mobile units. These will depend only on the distance between installations. The definition of routes is done through the mathematical formulation proposed by (Baldacci et al, 2004) for the Capacitated Vehicle Routing Problem, which was adapted to the needs of this problem. In this two-commodity flow formulation two flow variables are used, $y_{i,j}$ and $y_{j,i}$, and effectively only one trip is made in the section between (i, j). After simulating the location model previously demonstrated, the exact number of time intervals that each vehicle needs to stay in a given TMB for one year are known (given by the number of variables $Qm_{i,j,k,t,s}$ in a certain year), and these will be the inputs of the model. That is, the flow $y_{i,j}$ is translated into time intervals performed for the section (i,j). Each route is defined by two paths: one path from depot 0 (real depot) to warehouse n+1 (copy depot, which is a replica of the real one and is represented by the flow variable, $y_{i,j}$)and one path from warehouse n+1 to warehouse 0 (represented by the flow variable $y_{j,i}$). The model is based on the assumption that the set of vehicles considered is homogeneous, i.e. the simulation of transport costs for each typology is performed individually.

Mathematical Formulation

Sets

I Set of TMB locations i ∈ I

Indexes

i Entity TMBs - i = {0, e1,,...n+1}

Binary variables

$x_{i,j}$ Variable whose value is 1 if there is a route between node i and node j and 0 otherwise

Discrete variables and not negative variables

$y_{i,j}$ Variable that represents the flow of time intervals between the node i and the node j

Auxiliary variables in the objective function

QT Quantity of time intervals of the homogeneous fleet

Parameters

$d_{i,j}$ Distance between i and j, in km

NT_i Number of time intervals that vehicles need for processing in installation i, over the period of one year

V Number of homogeneous vehicles available

Q Time intervals in which the period of one year is divided

C Travel cost in euros per km

N Number of years in which these vehicles are processing

Objective function

Equation 41: Transport cost related to the transportation of mobile units

$$\min \;\; CTr = 0.5\left(\sum_{i\in I}\;\sum_{j\in I,(j\neq i)} x_{i,j} * d_{i,j} * C * N\right) \qquad [41]$$

Auxiliary equations

Equation 42: Relation between flows and number of vehicles in the system

$$\sum_{j\in I,(j\neq i)} (y_{i,j} - y_{j,i}) = 2NT_i \qquad [42]$$

Equation 43: Depot n+1 entry flow

$$\sum_{i\in I\backslash\{0,n+1\}} y_{i,n+1} = \sum_{i\in I\backslash\{0,n+1\}} NT_i \qquad [43]$$

Equation 44: Depot n+1 exit flow

$$\sum_{j\in I\backslash\{0,n+1\}} y_{n+1,j} = QT - \sum_{i\in I\backslash\{0,n+1\}} NT_i \qquad [44]$$

Equation 45: Total quantity of time intervals

$$QT = V * Q \qquad [45]$$

Equation 46: Depot 0 entry flow

$$\sum_{j\in I\backslash\{0,n+1\}} y_{i,0} \leq QT \qquad [46]$$

Equation 47: Depot 0 exit flow

$$\sum_{i\in I,(i\neq j)} y_{0,j} = 0 \qquad [47]$$

Equation 48: Entry and exit of vehicles in TMBs

$$\sum_{i \in I, (i \neq j)} x_{i,j} = 2 \qquad , \forall j \in I \backslash \{0, n+1\} \qquad [48]$$

Equation 49: Capacity restriction for each vehicle

$$y_{i,j} + y_{j,i} = Q * x_{i,j} \qquad , \forall i, j \in i, i \neq j \qquad [49]$$

The objective function [41] considers the minimization of the transportation cost T. Given that this is a two-commodity flow formulation, where two paths define a route, each edge is counted twice, therefore the total distance is multiplied by 0.5 to calculate the actual distance. Constraint [42] ensures that the outflow minus the inflow at each facility is equal to twice the amount of time intervals present in each one, since this formulation considers the existence of two flows passing through a node. Constraint [43] ensures that the total inflow of the copy depot is equal to the total amount of time needed in TMBs, while constraint [44] ensures that the total outflow of the copy depot is equal to the residual time of the vehicle fleet. Equation [45] defines the quantity of time intervals of the homogeneous fleet. Constraint [46] guarantees that the total inflow of the real depot is lower or equal to the number of processing intervals of the vehicle fleet and constraint [47] completes this by guaranteeing that the total outflow of the real depot is equal to zero. The existence of two edges incident to each TMB is ensured by constraint [48]. Constraint [49] links variables x and y, guaranteeing that the sum of the flows for every edge (i,j) must be equal to the vehicle's total processing intervals, that is, if the edge is actually traversed by a vehicle.

5. Results

To obtain a better analysis of the project in question, three general aspects have been outlined that will be further evaluated: 1) TMB installations to be included in the logistic system; 2) Quantity of heavy rejects to be processed; 3) Prediction of the percentage of glass in the heavy reject. Point 1) refers to the study of all existing TMBs in Portugal, or the study of only the facilities belonging to the EGF (Environmental Global Facilities) group, which makes up for 10 out of the 18 TMBs in Portugal. The analysis of the latter sub-group will make it possible to verify the financial viability of carrying out the project only in these facilities, which can benefit from a more integrated and cooperative system, in which the use of economies of scale as a means of reducing costs of the whole system can be advantageous. Point 2) considers the amount of reject to process: that can be in its totality, in which the reject of the whole system is forced to be processed, regardless of being profitable; or freely, that is, only the reject that is financially beneficial to the system is processed. Point 3) concerns the percentage of glass in the reject over the time horizon. This analysis is relevant, since its value can be expected to decrease in a phased manner in the coming years, due to the increase in the environmental awareness of the population and to a set of measures concerning waste collection that will be implemented in the coming years. This portion is characterized by four different scenarios s1, s2, s3 and s4, presented in Table 1.

Table 1: Estimate of percentage of glass present in Urban Waste Undifferentiated over the time horizon

Scenario	1 (2021)	2	3	4	5	6	7	8	9	10 (2030)
$Vp_{t,s1}$(%)	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$Vp_{t,s2}$(%)	100%	90%	90%	85%	85%	24%	24%	20%	20%	20%
$Vp_{t,s3}$(%)	100%	50%	30%	13%	13%	13%	10%	10%	10%	10%
$Vp_{t,s4}$(%)	100%	45%	27%	11%	11%	3%	2%	2%	2%	2%

To determine the adequate time period t of the location model performed, data concerning the daily processing capacities and the amount of TMBr to be processed in the smaller TMB was taken. It was assumed that the appropriate time interval would be an intermediate value of the days of processing required to drain all the product from this smaller installation. The time period obtained was approximately one month, so, for the purpose of this analysis, the length of time intervals was this one.

Firstly, the analysis of the project consisted in the optimization of the individual scenarios s1, s2, s3 and s4. Thus, to obtain the NPV values of the independent scenarios, a probability of 100% was assigned to the scenario to be analyzed and a probability of 0% was given to the remaining scenarios. In this study, conclusions were taken regarding the investments in diagrams: while scenarios s1 and s2 integrated a mixed approach, with TMBr being processed by fixed and mobile units, scenarios s3 and s4 reached the optimal network design by only investing in fixed diagrams. Additionally, the processing activities were taken in different time stamps through the different scenarios: s1 was profitable through all the 10 years of study, so, it recuperated glass throughout these years; scenario s2 only processed for 5 years; and scenarios s3 and s4 only recovered glass in the first 3 years of the project.

After the study of the independent scenarios, the stochastic model was applied to obtain the best combination of investment in the system considering all the scenarios of the evolution of glass in TMBr and its probabilities of event. These probabilities were presented by Sociedade Ponto Verde in value ranges, so the average of each set was used (see Table 2).

Table 2: Probability of Event for each Scenario (Source: SPV)

Stochastic Model		
Scenario	**Probability of Event**	***P (s)***
s1	[0 - 5] %	2,5%
s2	[5 - 10] %	7,5%
s3	[5 - 10] %	7,5%
s4	[80 - 85] %	82,5%

The logistic system defined by the model will be the one that mathematically better fits all the predictions of percentage of glass in the present reject over the years and its probabilities, allowing a higher expected NPV. The results obtained in the optimization of the stochastic model are present in Tables 3 and 4. The outputs of the model are divided by scenario, and the only value that is aggregated is the NPV value (objective function). Therefore, it was also performed the calculation of a weighted average of glass recovered, considering all the scenarios and the probabilities of event.

Table 3: Investment Results and NPV of the stochastic model

No. Processing Facilities	No. Fixed Diagrams	No. TMBs included in the system	No. Mobile Units	NPV
1	3	2	0	206 400 €

Table 4: Amount of recovered glass in stochastic model and weighted average calculation

Quantity of glass recovered (ton)				
Year/Scenario	**s1**	**s2**	**s3**	**s4**
1	16495,4	16495,4	16495,4	16495,4
2	16495,4	14845,87	5374,7	4837,2
3	16495,4	14845,87	3224,8	2902,3
4	16495,4	14021,1	-	-
5	16495,4	14021,1	-	-
6	16495,4	-	-	-
7	16495,4	-	-	-
8	16495,4	-	-	-
9	16495,4	-	-	-
10	16495,4	-	-	-
Total	164954	74229,34	25094,9	24234,9
Probability	2,5%	7,5%	7,5%	82,5%
Glass recovery	4123,85	5567,2005	1882,1175	19993,7925
Weighted average	**31566,9 ton**			

The optimal mixed logistic system obtained is, in fact, a purely fixed system, characterized by the existence of a fixed processing plant in which three diagrams are inserted. In this system, the reject from other TMB is also forwarded to this treatment plant, which is allowed due to the centralized characteristics of the fixed facilities. From Table 3 can be seen that the NPV value of 206 400€ is higher than the NPV values obtained in the processing scenarios of s3 and s4 and lower than those of the scenarios s1 and s2. This is because the probabilities of events associated with scenarios s1 (2.5%) and s2 (7.5%) are lower than those recorded in s4 (82.5%). Scenario s3 (7.5%), although it has an equally low probability, is a scenario with values close to those recorded in scenario s4, thus the difference in the NPV value obtained between the two are small. The weighted average of the recovered glass is also higher than those recorded in the independent scenarios s3 and s4 and lower than those of s1 and s2.

6. Sensitivity analysis

The following sensitivity analyses are intended to add robustness to the system study. They will consist of the variation of parameters of the model that are susceptible to be modified considering the context of the project. Since the information regarding the percentages of glass in the reject was provided by SPV in the form of a range, the changes to the parameters will be applied to the stochastic model in the form of three different scenarios, presented in Table 5:

Table 5: Sensitivity Analysis Scenarios

Sensitivity Analysis				
Scenario	**s1**	**s2**	**s3**	**s4**
	[0 – 5] %	**[5 – 10] %**	**[5 – 10] %**	**[80 – 85] %**
A (Probable)	2,50%	7,50%	7,50%	82,50%
B (Optimistic)	5%	10%	5%	80%
C (Pessimistic)	0%	5%	10%	85%

The explanation of the new scenarios is as described: scenario A - scenario in which the average of the existing probability intervals is used. This was the scenario studied in section 5.5; scenario B - optimistic scenario regarding the evolution of the glass percentage, since it includes the maximum value of the probability intervals registered in s1 and s2 - which are the ones with the highest values - and the lowest values of the intervals presented for s3 and s4; scenario C - pessimistic scenario, where the inverse reasoning to that presented in B was used, i.e., using the maximum values registered in s3 and s4 and the minimum values present in s1 and s2.

Price of recovered glass (Pu)

Legally the return value of glass recovery in TMB installations is 71 € /ton. However, it is expected that this value will decrease, as the initiatives planned in the coming years are intended to encourage TMBs to be more effective in selective collection and, as such, the recovery of undifferentiated collection materials will not be prioritized. Additionally, if the project is at the expense of an external entity, this return price will be much lower.

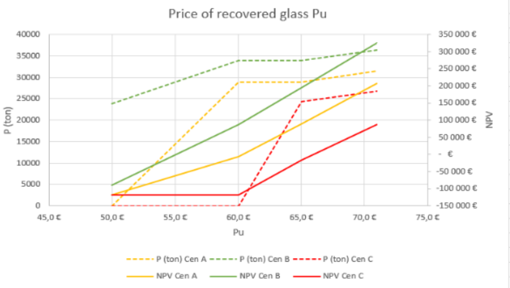

Figure 1: Pu Sensitivity Analysis

From the sensitivity analysis of Figure 1, it was concluded that the higher the recovery price of the glass, the higher the NPV and the amount of glass recovered in the system. The price for glass recovery from landfill operations could range from 55 to 65 € /ton to ensure the financial viability of the project, depending on the context verified.

Cost of External Landfill (Aex)

The parameterization of external landfill costs in the model is made on the assumption that the project is under the responsibility of the TMBs, which means that its value is in the order of 8 € /ton. In fact, this may not be the context in which the project will be applied, with the hypothesis that the project is under the responsibility of an external entity. In this case, according to values provided by Maltha Glass Recycling Portugal, this cost may vary between [46-64] € /ton.

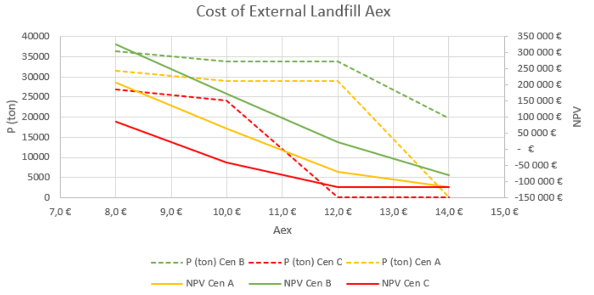

Figure 2: Aex Sensitivity Analysis

From Figure 2 it can be verified that the increase in the cost of external landfill has an opposite effect to the one registered in the return price of the glass, that is, the higher the value of this cost, the lower the NPV of the project and the amount of glass recovered. The cost of external landfill may vary between 10 and 12 € /ton, depending on the context. Considering that the cost of external landfill can reach 46 € /ton, in case the project is under the responsibility of an external entity, one can conclude that a business model that includes TMBs as responsible for these activities will be necessary, and, if this does not happen, it is not possible to have a profitable system capable of recovering glass from this stream.

Diagrams's Effectiveness (E)

The last parameter to be evaluated is the efficiency in the diagrams, whose established value was 80%, assuming a set of optimal conditions for its processing (such as the correct drying of the whole product). It will be expected that the recorded assumption is subject to variations, not only by the complexity of the processes performed, but also by the diverse nature of TMBr, which depending on TMBs to TMBs, holds various compositions and granulometries.

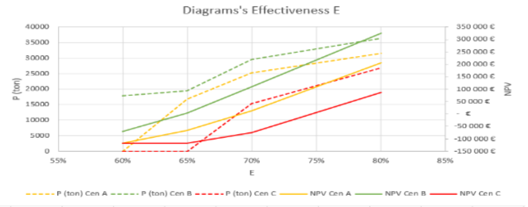

Figure 3: E Sensitivity Analysis

From the analysis of Figure 3 it can be verified that the greater the efficiency of the system diagrams, the higher the value of the NPV and the amount of glass recovered. The effectiveness of the diagram can register minimum values between 65 and 75%, depending on the context. Since these are somewhat high efficiency values, it will be necessary to ensure that the reject introduced into these diagrams is in the best possible condition.

7. Conclusions

The recovery of packaging glass has proven to be a challenge for Portugal, so the implementation of a project in this context would be advantageous. The dissertation presented intends to assist this implementation process, arriving at a financially viable solution from the design and planning point of view of the desired mixed logistics system. It should be noted that this study is still insufficient for the implementation of this system, since to achieve economic and operational viability, the collaboration of all entities involved is necessary. Of the logistic system approaches: fixed and/or mobile, the fixed system proved to be the most advantageous, being the one that ensures a higher expected NPV when considering all the percentage of glass scenarios presented. The fact that the system allows the displacement of the reject from other TMBs to the processing facilities turns out to be an advantageous factor, which is regularly verified in the results of the model. The sensitivity analyses also concluded that one of the priorities is the integration of TMBs in the defined business model to take advantage of the same price values per ton of glass recovered and lower external landfill costs. If this business model is not guaranteed, the feasibility of the project cannot be assured.

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