New approach for optimization of construction and demolition waste management (with time component)

Application to the Lisbon Metropolitan Area

Fernando Galimberti Braga[1]

[1] Master in Industrial Engineering Management, Instituto Superior Técnico, Universidade de Lisboa - Portugal

Abstract

The impacts caused by construction and demolition waste (CDW) can be high if it is not managed effectively. Consequently, the concerns related to this management have increased in recent years, stimulating the development of studies on the subject.This dissertation intends to continue the work of Correia (2013) and Andrade (2015), who developed a new approach for the planning of a CDW recycling network, using a mixed integer linear programming model that aims to minimize costs. In this work a temporal component is added to the mathematical formulation, which makes it possible to model the material flows between the various processes for each of the periods of the time horizon considered.

The model is validated using a reduced data set, considering only 10 parishes, and is then applied to the 211 parishes that make up the Metropolitan Area of Lisbon (MAL), with the generation of multiple scenarios and a sensitivity analysis of the most relevant parameters. Although it was applied at regional level, the formulation is generic to the extent that it can be used at national level.The results obtained indicate that, from an economic point of view, it is more viable to landfill CDW than to recycle. Furthermore, it can be concluded that the cost of landfilling waste has a high influence on the amount of CDW recycled.

Keywords: Construction and demolition waste, mixed integer linear programming, optimization model, Metropolitan Area of Lisbon.

1. Introduction

A huge amount of construction and demolition waste (CDW) is produced every year, with much of it having the potential to be recycled (Wu et al., 2019). In the European Union (EU) alone, more than 920 million tonnes of CDW were produced in 2016, corresponding to 36% of the total waste produced in the region (Eurostat, 2020), which shows that proper management of this waste is necessary and extremely important, especially in the environmental aspect.

However, the management of this type of waste is complicated by several factors, starting with its composition, since CDW presents a heterogeneous constitution, with materials of various sizes and hazard levels. In addition, construction, remodelling and demolition activities are geographically dispersed and temporary, which makes it difficult for the competent authorities to supervise them. Added to the factors cited, the consumption of finite natural resources, the illegal disposal of CDW and the lack of space to create landfills in some regions has led to an increase in the number of studies and legislation on the CDW management, aimed at reducing environmental impacts in an economically viable way.

The first attitude taken by the EU was the approval of the Directive (2008/98/EC), which stipulates as a target for 2020 that Member States prepare for reuse, recycling and recovery at least 70% by weight of non-hazardous CDW. Therefore, Decree-Law No. 46/2008 (later amended by DL No. 73/2011) was approved in 2008 in Portugal, aiming to transpose this directive and draw up a specific management regime for CDW, helping the country to achieve the target set by the European Parliament.

According to Sáez & Osmani (2019), Portugal treated less than 60% of the total CDW generated in 2012, while Deloitte (2017) claims that this figure is higher than the 70% established by the EU. This discrepancy in values is mainly related to the fact that most construction companies are small or medium sized, making much of the waste production unknown, indicating that CDM needs to be improved.

Based on this scenario that this work is developed, since optimization models of the CDW recycling network can be crucial instruments in the pursuit of the goals stipulated by government entities, intending to minimize the costs of the processes caused by the production and management of waste.

2. CDW characterization

As already mentioned, CDW is responsible for a significant part of the waste produced in Portugal and in the rest of the EU, being generated in large quantities, and with a high potential for recovery (often wasted). In addition, the construction sector is responsible for 24% of extracted natural resources, again demonstrating the environmental weight that this waste has (Carrola, 2017).

This waste can be characterized as waste from construction, reconstruction, extension, alteration, conservation and demolition works and from the collapse of buildings (Decree Law No. 73/2011).

One of the main factors that hinders the management of CDW is directly related to its heterogeneity. This type of waste is composed by different types of materials, with various dimensions and hazard levels. This heterogeneous composition can be linked to some aspects, such as the different methods and techniques that exist and can be used in each country and region. Another aspect that may cause diversity in CDW is the type of work:

- In construction works, the composition of the waste will depend on the materials used, in addition to the methods and techniques.
- In the case of demolition works, on the other hand, more factors affect the waste composition, such as the materials and methods that were used at the time of the construction of the structure being demolished, the type of use the structure had and, mainly, the degree of waste management and separation during demolition.
- The waste originated in repair works has a composition that varies greatly, depending on whether it will be a remodelling, rehabilitation or renovation work.

The European Waste List, which was cited in the previous chapter and is present in Decision 2014/955/EU, separates CDW as follows:

- Concrete, bricks, tiles, roof tiles and ceramic materials.
- Wood, glass and plastic.
- Bituminous mixtures, tar and tar products.
- Metals (including metal alloys).
- Soil (including excavated soil from contaminated sites), rock and dredging spoil.
- Insulation materials and construction materials containing asbestos.
- Gypsum-based construction materials.
- Other construction and demolition wastes.

3. Literature Review

There are several articles concerning waste management optimization models, such as urban or electronic waste for instance. However, models applied specifically to CDW management are more recent, with the one developed by Hiete et al. (2011) being one of the pioneers in this field A brief description of these models is given in Table 1, and further analysis follows

Table 1 – Description of the optimization models in the literature

Author	Title	Description
Hiete et al. (2011)	Matching construction and demolition waste supply to recycling demand: a regional management chain model	Optimisation model with focus on cost minimisation in the planning of a regional network for CDW recycling, applied in south-west Germany.
Galan et al. (2013)	Optimisation of the construction and demolition waste management facilities location in Cantabria (Spain) under economical and environmental criteria	Model with the objective of identifying the best location for recycling plants and sorting stations, with the aim of minimising the average transport distance and total costs. Model applied in Cantabria, Spain.
Correia (2013)	Optimização da gestão de resíduos de construção e demolição: Aplicação à Área Metropolitana de Lisboa	Model that aims to expand the model of Hiete et al. (2011), including a methodology for assessing environmental impacts. Model applied to the Lisbon metropolitan area at the county level.
Andrade (2015)	Nova abordagem para a optimização da gestão de resíduos de construção e demolição: Aplicação à Área Metropolitana de Lisboa	Model aiming at improving Correia's (2013) model, with a more extensive and complete data collection, and being applied to the Lisbon metropolitan area at parish level.
AlZaghrini et al. (2019)	Using GIS and optimization to manage construction and demolition waste: The case of abandoned quarries in Lebanon	Decision support tool for developing countries focusing on selecting abandoned quarries to serve as recycling plants and landfills for CDW. Model applied in two regions of Lebanon (Beirut and Mount Lebanon).
Xu et al. (2019)	Reverse Logistics Network-Based Multiperiod Optimization for Construction and Demolition Waste Disposal	Model that employs the reverse logistics network aimed at optimising CDW disposal processes, reducing costs and environmental pollution. Model demonstrated in China, in multiple waste disposal centres.

The optimization model developed by Hiete et al. (2011) allows the planning and evaluation of a regional network of CDW recycling. This model aims to minimize costs, evaluate environmental performance, and present the effects caused by intervention policies. Thus, the model of Hiete et al. (2011) determines what would be the optimal configuration of the CDW network, and considered the following aspects:

- Waste flow between the CDW producers and the landfills or recycling plants.
- Waste flow between recycling plants and landfills or sites with demand for recycled aggregates.
- Capacity of recycling plants.

- Fixed and variable costs.

Hiete et al. (2011) applied the model in southwest Germany, more specifically in the federal state of Baden-Württtenmberg. The model corresponds to a Mixed Integer Linear Programming (MILP) problem and was implemented in the Generic Algebraic Modeling System (GAMS).

Subsequently, Galan et al. (2013) developed an optimization model whose objective is to identify the location and capacity of recycling plants and sorting stations of a CDW management in order to minimize the average transport distance and total management costs (installation, operation and disposal costs). The CDW management network of this model is composed of CDW producers, sorting plants, recycling plants, inert CDW landfills and the market that uses the recycled aggregates. The material flow that was considered is illustrated in figure 10, where CDW producers can send their waste directly to the recycling plants or to the sorting plants. The plants generate two types of materials, the non-recyclable materials that are sent to landfills, and the recyclable aggregates that can be sold in the market. Sorting stations segregate CDW so as to increase process efficiency and reduce operating costs by sending what cannot be recycled directly to landfill and sending what can be recycled to recycling plants.

Another method of optimising the management of CDW is through the reverse logistics network, and Xu et al. (2019) characterise the structure of this network as follows:

- The network starts with the producers of CDW and ends with the manufacturers of materials, focusing on the regeneration of the materials.
- Reverse logistics collects the materials at the end of the supply chain and runs them through the various nodes of the reverse chain that successively regenerate the state of the materials to obtain the reusable product.
- This ensures that the waste is not incinerated or dumped in landfills, reducing environmental impacts.

Therefore, Xu et al. (2019) employed a reverse logistics network along with a mathematical optimization method (MILP model implemented in MATLAB software), aiming to improve recycling and reduce both environmental pollution and disposal costs of CDW. The structure of the network used in the study, illustrated in Figure 11, considers that CDW is first collected at the construction sites, followed by a central sorting and collection centre, where the waste is classified in order to know whether it is recyclable or not. CDW that cannot be recycled is transported to disposal sites, while recyclable CDW is taken to dismantling centres. Finally, the materials are sent to material manufacturers, thus returning to the beginning of the supply chain.

4. Mathematical programming model definition

4.1 Problem Statement

In continuity to the model developed by Andrade (2015) and seeking to deepen the approach according to the principles of Process and Systems Engineering (PSE), it is added in this work the temporal component. Initially it was considered to define the seasonality according to the seasons of the year, but after contact via email with some companies of RCD, the company Renascimento provided the seasonality of waste receipt at their facilities, and it was found that the best modelling option would be to divide the year into 12 periods, i.e., in a monthly manner, since the data received were in this format. Thus, in this work, 12 periods are considered, thus corresponding to a year.

According to the information obtained, the months of January and December are the months with the lowest flow of materials, adding up to 10% of the year's waste. May, June, July and August are the months with the highest incidence of materials, totalling in these four months half the amount of annual waste. Finally, the remaining 40% of CDW produced annually are distributed in the six months not mentioned.

Table 2 presents the percentage values of CDW production in each of the months. Because of the periodic infinite decimal caused by the 40% distributed over six months, it was necessary to make an approximation so that the sum of percentages would give 100% and would not affect the model. Thus, the percentage values used are those of the third column (% used).

Table 2 – Percentage of monthly CDW production (Data provided by the company Renascimento and percentage used in the model)

Month	%	% used
January	5.00	5.00
February	6.67	6.70
March	6.67	6.70
April	6.67	6.70
May	12.50	12.45
June	12.50	12.45
July	12.50	12.45
August	12.50	12.45
September	6.67	6.70
October	6.67	6.70
November	6.67	6.70
December	5.00	5.00
Total	100.02	100.00

Differently from Hiete et al. (2011) and Correia (2013), who considered plants to be fixed facilities, without modelling the processes that took place at the facilities, Andrade (2015) disaggregated the main processes that occur at sorting and recycling plants. As can be seen in Figure 1, recycling plants have two or three processes, which are: incorporated sorting, low quality recycling (LQ) and HQ recycling (there are plants that do not have HQ recycling, having only the two initial processes).

Figure 1 – Scheme of each facility processes (Andrade, 2015)

- Network nodes characterised by the following attributes:
    - CDW production
    - Demand of processed materials
    - Number and types of recycling plants (RP)
    - Number of landfills
- Arcs defined for all pairs of nodes, with each arc associated with the distance between the corresponding pair of nodes.
- Cost of transportation as a function of the distance between nodes.
- Landfilling cost of CDW and residual materials.
- Sale value of sold products.
- Different types of RP (type of plants differentiated by capacity and transformation characteristics). It was considered in the model that pre-existing RPs can not be closed and that new plants can be built, as long as each node has a maximum of one plant of each type.
- Capacity, investment cost (in the case of new RP construction) and variable costs per type of CR.
- Unlimited capacity of the landfill areas (hypothesis assumed since these capacities were not available).

According to the objective function to be studied, the following decisions are possible:

- Installation of new processes (Type, capacity and location).
- Material flow in the network.

Figure 2 shows the layout, materials and processes that are considered in the model, and it is possible to observe the connection between the different materials and the existing processes. It should be noted that the dashed arrows represent that the material has more than one possible destination, which is the case for CDW (can go to sorting or landfill) and S10 (can go to HQ recycling or be sold).

It is important to highlight that if not landfilled, materials S2 and S1 should follow the following sequence: S2⇒S4⇒S9 and S1⇒S3⇒S10⇒S11, the latter being that S10 can either be sold or processed (originating S11).

The scheme in figure 2 shows the entire chain of processes, where materials are represented by "S" and processes by "k". CDW, which are S1 (concrete) and S2 (undifferentiated material), can be treated or landfilled. If treated, they must first go through sorting (k1) or incorporated sorting (k2), resulting in waste material (MR1), materials that will be sold (S5, S6, S7 and S8), in addition to S3 (sorted concrete) and S4 (sorted undifferentiated), which go on to the LQ recycling process (k3). From k3, materials for sale, residual matter (only MR2 in this case), S9 (undifferentiated LQ) that will be sold and S10 (LQ concrete) are originated again. Then there are two options for S10, which are sale or HQ recycling (k4). Finally, the k4 process will produce MR2 and products that will be sold, including S11 (HQ concrete).

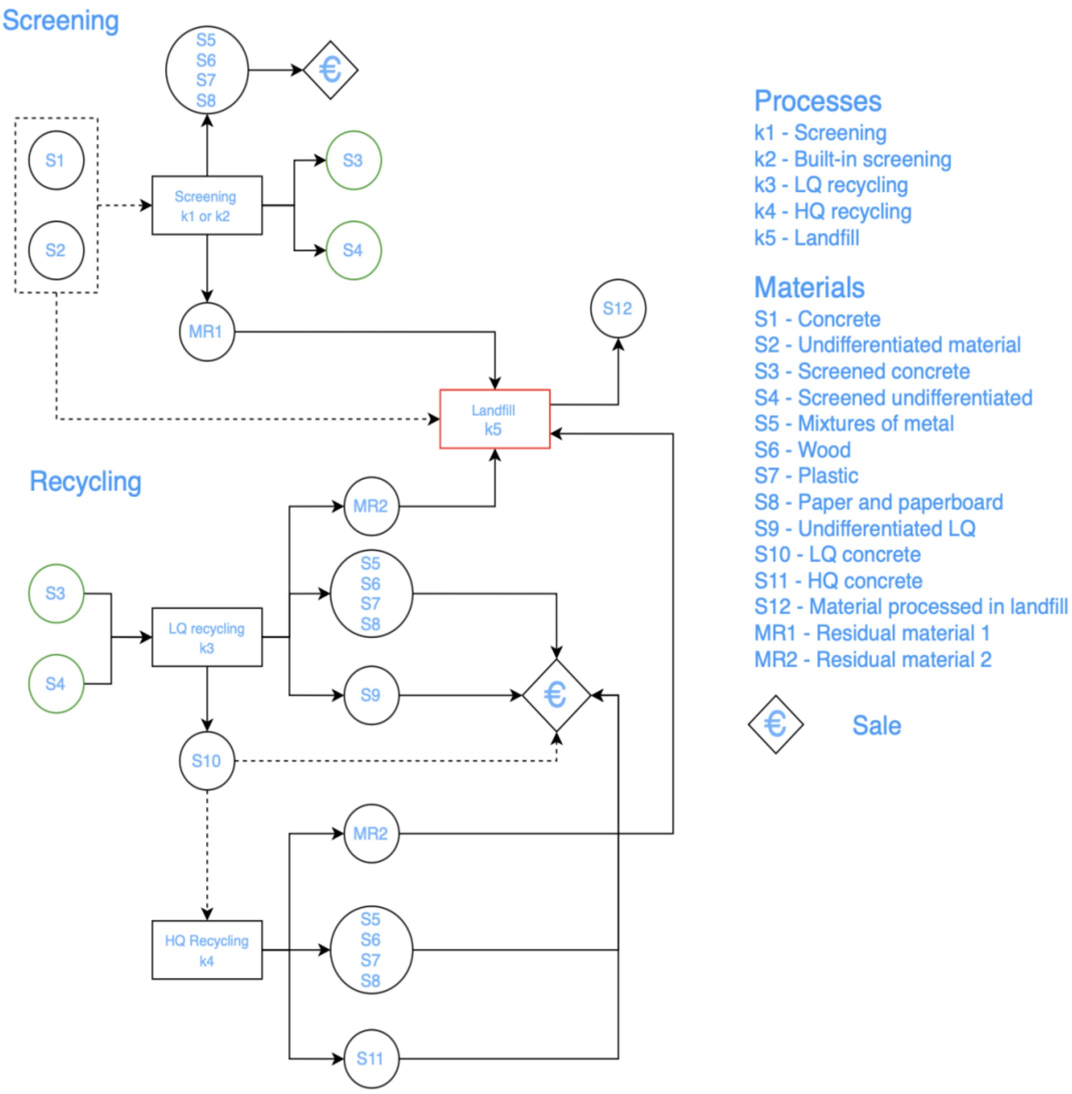

Figure 2 – Layout, materials and processes

4.2 Mathematical formulation of the model

The problem under study can therefore be modelled by the following mathematical programming formulation.

4.2.1 Sets

$i, j \in I$	Set of network nodes
$s, s' \in S$	Set of material states
$RCD \subset S$	Subset of CDW
$PI \subset S$	Subset of intermediate products
$PV \subset S$	Subset of sold products
$MR \subset S$	Subset of residual materials
$k, k' \in K$	Set of processes
$kc \in KC$	Set of maximum capacities considered for the process k
$t \in T$	Set of time periods
$Iks_{k,s}$	Set of input material s in process k
$Oks_{k,s}$	Set of output material s in process k

4.2.2 Parameters

cda_s	Landfilling cost of material s (€/ton) $\forall s \in RCD \cup MR$
e_s	Sale value of material s (€/ton) $\forall s \in PV$
u_s	Global demand of material s (€/year) $\forall s \in PV$
$b_{i,j}$	Cost of transporting a material from node i to node j (€/ton) $\forall i, j \in I$
$h_{i,s}$	Quantity of material s produced at node i annually (ton/year) $\forall i \in I;\ s \in RCD$
$Perce_t$	Defines the seasonality of CDW production in each period t (%) $\forall t \in T$

$ht_{i,s,t}$	Quantity of material s produced at node i in period t, based on parameter $Perce_t$ (ton/month) $\forall i \in I;\ t \in T;\ s \in RCD$
$v_{k,s,s'}$	Proportion of material s´ obtained from material s in process k (%) $\forall k \in K;\ (s,s') \in S$
$cp_{k,s}$	Processing cost of material s in process k $\forall k \neq K;\ s \notin RCD$
$yp_{i,k}$	Pre-existing processes k at node I (if process k exists at node i, $yp_{i,k}$=1, otherwise $yp_{i,k} = 0$) $\forall i \in I;\ k \in K$
$kup_{k,i}$	Capacity of pre-existing processes k at node i (ton/month) $\forall i \in I;\ k \in K$
$kkc_{kc,k}$	Available capacities kc to install new processes k (ton/month) $\forall kc \in KC;\ k \neq (k0, k5)$
$ikc_{k,kc}$	Cost of installing a kc capacity for process k (€) $\forall kc \in KC;\ k \neq (k0, k5)$
$Xrec$	Scalar that defines the minimum percentage of CDW that must be recycled
$Lig_{k,k'}$	Determines the possible k' processes that come after process k $\forall k \neq k5;\ k' \neq k0$

4.2.3 Variables

$Custo$	Total cost of CDW recycling network (€)
$CustoAterro_t$	CDW landfill cost in period t (€)
$CustoProc_t$	Cost of CDW in recycling processes in period t (€)
$Proc1_t$	Operating cost of all processes in period t, including transport cost (€)
$Proc2_t$	Cost of landfilling residual materials in period t, including transport cost (€)
$Proc3_t$	Revenue from the sales of sold products in period t (€)
$Proc4_t$	Investment cost for new processes in period t (€)
$Q_{s,i,j,k,k',t}$	Quantity of material s that comes from process k at node i and enters on process k' at node j, in period t (ton/month)
$Qrec$	Minimum amount of CDW that must be recycled (€/year)
$Qate$	Maximum amount of CDW that can be landfilled (€/year)
$Hdep_{i,s,t}$	Quantity of CDW available to be recycled or landfilled in period t. This variable is the sum of the CDW produced in period t with the CDW that was not recycled or landfilled in previous periods (ton)
$X_{s,i,k,t}$	Quantity of material s sold at node i that comes from process k in period t (ton)
$KKI_{k,i,t}$	Installed capacity of process k at node i in period t, considering pre-existing and new capacities (ton/month)
$IKI_{k,i,t}$	Investment cost related to installing a process k at node i in period t (€)
$Y_{k,i,t}$	Binary variable that defines whether process k exists at node i in period t: • $Y_{k,i,t}$= 1 if process k is installed at node i in period t • $Y_{k,i,t}$= 0 otherwise
$YC_{k,kc,i,t}$	Binary variable that selects the maximum capacity kc of process k at node i in period t: • $YC_{k,kc,i,t}$= 1 if process k has maximum capacity kc at node i in period t • $YC_{k,kc,i,t}$= 0 otherwise

4.2.4 Model Formulation

The mathematical model for planning the CDW recycling network is presented next:

$$Minimize\ Custo = \sum_{t \in T} CustoProc_t + \sum_{t \in T} CustoAterro_t \quad \forall t \in T \qquad \textbf{[1]}$$

Subject to:

$$CustoAterro_t = \sum_{i \in I} \sum_{j \in I} \sum_{s \in RCD} \left(cda_s + b_{i,j}\right) * Q_{s,i,j,k,k',t} \quad \forall t \in T;\ k = k0;\ k' = k5 \qquad \textbf{[2]}$$

$$CustoProc_t = Proc1_t + Proc2_t - Proc3_t + Proc4_t \quad \forall t \in T \qquad \textbf{[3]}$$

$$Proc1_t = \sum_{k' \neq (k0,k5)} \sum_{s \in iks_{k',s}} \sum_{k \in oks_{k,s}} \sum_{i \in I} \sum_{j \in I} Lig_{k,k'} * \left(b_{i,j} + cp_{k',s}\right) * Q_{s,i,j,k,k',t} \quad \forall t \in T \qquad \textbf{[4]}$$

$$Proc2_t = \sum_{s\in MR}\sum_{k\in oks_{k,s}}\sum_{i\in I}\sum_{j\in I}\left(cda_s + b_{i,j}\right) * Q_{s,i,j,k,k',t} \quad \forall t \in T;\ \ k' = k5 \qquad [5]$$

$$Proc3_t = \sum_{k\neq(k0,k5)}\sum_{i\in I}\sum_{s\in\left(PV\cap oks_{k,s}\right)} X_{s,i,k,t} * e_s \quad \forall t \in T \qquad [6]$$

$$Proc4_t = \sum_{k\neq(k0,k5)}\sum_{i\in I} IKI_{k,i,t} \quad \forall t \in T \qquad [7]$$

$$Y_{k,i,t} \ \geq\ yp_{i,k} \quad \forall k \neq (k0,k5);\ i \in I;\ t = t1 \qquad [8]$$

$$Y_{k,i,t} \ \geq\ Y_{k,i,t-1} \quad \forall k \neq (k0,k5);\ i \in I;\ t \neq t1 \qquad [9]$$

$$\sum_{kc\in KC} YC_{k,kc,i,t} = Y_{k,i,t} \quad \forall k \neq (k0,k5);\ i \in I;\ t \in T \quad se\ yp_{i,k} = 0 \qquad [10]$$

$$YC_{k,kc,i,t} \ \geq\ YC_{k,kc,i,t-1} \quad \forall k \neq (k0,k5);\ i \in I;\ kc \in KC;\ t \neq t1 \quad se\ yp_{i,k} = 0 \qquad [11]$$

$$Y_{k,i,t} = yp_{i,k} \quad \forall i \in I;\ t \in T;\ k = k5 \qquad [12]$$

$$KKI_{k,i,t} = \sum_{kc\in KC} kkc_{kc,k} * YC_{k,kc,i,t} \quad \forall k \neq (k0,k5);\ i \in I;\ t \in T \quad se\ yp_{i,k} = 0 \qquad [13]$$

$$KKI_{k,i,t} = kup_{k,i} \quad \forall k \neq (k0,k5);\ i \in I;\ t \in T \quad se\ yp_{i,k} = 1 \qquad [14]$$

$$KKI_{k,i,t} = kup_{k,i} * yp_{i,k} \quad \forall i \in I;\ t \in T;\ k = k5 \qquad [15]$$

$$IKI_{k,i,t} = \sum_{kc\in KC} ikc_{k,kc} * YC_{k,kc,i,t} \quad \forall i \in I;\ k \neq (k0,k5);\ t = t1 \quad se\ yp_{i,k} = 0 \qquad [16]$$

$$IKI_{k,i,t} = \sum_{kc\in KC} ikc_{k,kc} * \left(YC_{k,kc,i,t} - YC_{k,kc,i,t-1}\right) \quad \forall i \in I;\ k \neq (k0,k5);\ t \neq t1 \quad se\ yp_{i,k} = 0 \qquad [17]$$

$$\sum_{k\neq(k0,k5)}\sum_{i\in I} X_{s,i,k,t} \leq u_s \quad \forall s \in PV;\ t \in T \qquad [18]$$

$$\sum_{s\in iks_{k',s}}\sum_{i\in I}\sum_{k\in oks_{k,s}} \left(Lig_{k,k'} * Q_{s,i,j,k,k',t}\right) \leq KKI_{k',j,t} \quad \forall k' \neq k0;\ j \in I;\ t \in T \qquad [19]$$

$$Qrec \geq Xrec * \sum_{s\in RCD}\sum_{i\in I} h_{i,s} \qquad [20]$$

$$Qate \leq (1 - Xrec) * \sum_{s\in RCD}\sum_{i\in I} h_{i,s} \qquad [21]$$

$$Qrec + Qate = \sum_{s\in RCD}\sum_{i\in I} h_{i,s} \qquad [22]$$

$$Qrec = \sum_{i\in I}\sum_{s\in RCD}\sum_{j\in J}\sum_{k'\in(k2,k3)}\sum_{t\in T} Q_{s,i,j,k,k',t} \quad para\ k = k0 \qquad [23]$$

$$Qate = \sum_{i\in I}\sum_{s\in RCD}\sum_{j\in J}\sum_{t\in T} Q_{s,i,j,k,k',t} \quad para\ k = k0; k' = k5 \qquad [24]$$

$$Hdep_{i,s,t} = ht_{i,s,t} \quad \forall i \in I;\ s \in RCD;\ t = t1 \qquad [25]$$

$$Hdep_{i,s,t} = ht_{i,s,t} + Hdep_{i,s,t-1} - \sum_{j\in I}\sum_{k'\in(k1,k2,k5)} Q_{s,i,j,k,k',t-1} \quad \forall i \in I;\ s \in RCD;\ t \neq t1;\ k = k0 \qquad [26]$$

$$\sum_{k'=(k1,k2,k5)}\sum_{j\in I} Q_{s,i,j,k,k',t} = Hdep_{i,s,t} \quad \forall s \in RCD;\ k = k0;\ i \in I;\ t \in T \qquad [27]$$

$$\sum_{s\in iks_{k',s}}\left(v_{k',s,s'} * \sum_{k\in oks_{k,s}}\sum_{i\in I} Lig_{k,k'} * Q_{s,i,j,k,k',t}\right) = X_{s',j,k',t} + \sum_{k\in iks_{k,s'}}\sum_{i\in I} Q_{s',j,i,k',k,t} \qquad [28]$$
$$\forall j \in I;\ k' \neq k0;\ s' \in oks_{k',s'};\ t \in T$$

The objective function [1] minimizes the total cost and is subdivided into landfilling cost and processes cost. Expression [2] is the cost of direct landfilling of CDW. Equation [3] calculates the cost of the recycling process and is divided into three costs and one revenue. The expressions for these four terms are:

1. Expression [4]: operating cost of the various processes, including the transportation cost.
2. Expression [5]: landfilling cost of residual materials, including transportation cost.
3. Expression [6]: revenue from sale of processed materials.
4. Expression [7]: investment cost for new processes.

Constraint [8] guarantees that all pre-existing processes at node i must remain open in first period, and constraint [9] ensures that pre-existing or new processes at node i must be open in subsequent periods.

Expression [10] defines that only one of the kc capacities can be selected when a new process k is installed at node i. Constraint [11] forces that process capacities selected in previous periods must be maintained, while equation [12] ensures that no new landfills can be open.

Constraints [13]-[15] define the variable $KKI_{k,i,t}$ values. When $yp_{i,k} = 0$ (there is no pre-existing process k at node i) $KKI_{k,i,t}$ assumes the capacity selected by $YC_{k,kc,i,t}$ variable in equation [10]. When $yp_{i,k} = 1$ (pre-existing process k at node i), $KKI_{k,i,t}$ assumes the value of parameter $kup_{k,i}$. Finally, when k=k5, variable $KKI_{k,i,t}$ assumes the value of $kup_{k,i}$ if exists landfill at node i.

Constraints [16] and [17] define the investment cost variable value ($IKI_{k,i,t}$). In period t1, if there is no pre-installed process k ($yp_{i,k} = 0$), $IKI_{k,i,t}$ assumes value $kup_{k,i}$ if $YC_{k,kc,i,t}$ = 1. From period t2 onwards, if there is no pre-installed process k ($yp_{i,k} = 0$), $IKI_{k,i,t}$ assumes value $kup_{k,i}$ selected by $YC_{k,kc,i,t}$ = 1. Constraint [17] has the purpose of not considering the doubled investment cost, thus existing the difference between the variables $YC_{k,kc,i,t}$ and $YC_{k,kc,i,t-1}$.

Constraint [18] limits sales according to demand and expression [19] states that the total quantity of materials processed is limited by the capacity of process k installed at node j.

Constraints [20]-[22] derive from the imposition of a minimum amount of CDW to treat, according to the value of $Xrec$. For example, to follow the European decree of treating 70% of CDW produced, $Xrec$ receives the value of 0.7. In this example, expression [20] establishes that the amount of recycled CDW is equal or higher than 70% of the total, expression [21] limits the amount of landfilled CDW to a maximum of 30% of the total and finally the equation [22] sums the two previous quantities so that all CDW produced is either treated or landfilled.

Equation [23] equates the value of the variable $Qrec$ to the flow of materials $Q_{s,i,j,k,k',t}$ going to recycling and expression [24] equates the value of the variable $Qate$ to the flow of materials $Q_{s,i,j,k,k',t}$ going to landfill.

Expression [25] defines the amount of available CDW ($Hdep_{i,s,t}$) in period t1 for treatment or landfilling, while equation [26] defines the amount of available CDW for treatment or landfilling from period t2 onwards.

Equation [27] represents the initialization of the material flow (virtual process k0 that represents the amount of CDW produced at each node), i.e., it is the mass balance of the CDW at node i in period t. Finally, equation [28] presents the global mass balance at node i, for each process k' and material s' in period t.

5. Results

The model formulation is a mixed-integer linear programming, applied to MAL, was implemented in GAMS 33.2.0 and solved through the CPLEX solver version 12.10.0.0, which uses a branch and bound algorithm to reach optimization. The experiments were conducted on an Intel® Core™ i7 CPU, 3610 MQ, with 2.3 GHz and 16.0Gb of RAM.

5.1 Scenarios and sensitivity analysis

Scenario A, which serves as the basis for the analysis of the remaining scenarios, has the obligation to recycle a minimum of 70% of CDW and is analysed below. The CDW production used in the model was estimated by Bernardo (2013), the distribution of CDW flows collected from Coelho (2012), the investment cost for the installation of new processes calculated by Andrade (2015) and other data collected by the author of the paper. Figure 3 shows the material flowchart for this scenario A.

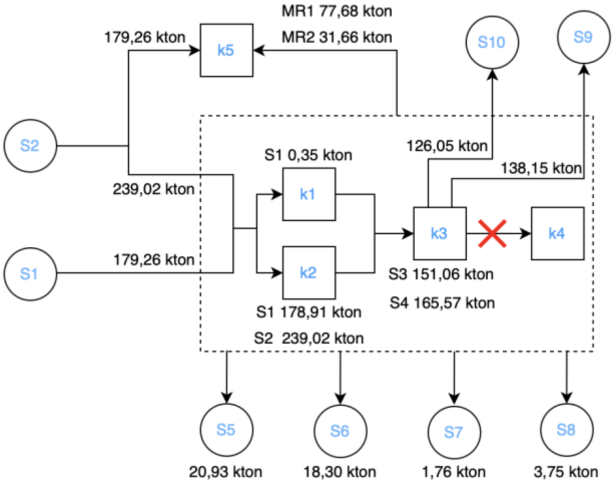

Figure 3 – Material flowchart for scenario A

While all S1 waste is recycled, S2 goes to both landfill and recycling. This is due to the higher cost of processing undifferentiated material, and it is more profitable to landfill S2 than S1. Regarding processes, no k4 process is installed, and all six pre-existing incorporated sorting and recycling LQ plants are used, reducing transport costs, as waste is thus sent to the nearest plant to its production nodes.

Table 3 presents the main output data of the scenarios analysed in this paper. Scenario A works as the base scenario and in the second scenario the obligation of minimum amount of recycled waste is removed. Scenario C defines that at least one k4 process must be installed, in D the proportions of S1 and S2 defined by Coelho (2012) are varied and in scenario E the capacities of the pre-existing plants are reduced to 20%. For Scenarios F-U a sensitivity analysis was carried out in order to observe the influence that some parameters have on the model. For the scenarios F to Q positive and negative variations of 20% are made to the parameters and from R to U gradual increases of 20% are made in the landfilling cost of CDW.

Table 3 – Main results obtained in the various scenarios (the symbol "*" means that there is no recycling obligation)

Scenario	Parameters/ Constraints	k1	k2	k3	k4	Recycling rate (%)	Capacity used (%)	Processing cost (M€)	Direct landfill cost (M€)	Total cost (M€)	Total cost (%)
A	-	11	6	6	0	70.0	24.5	13.16	3.89	17.05	100.0
B*	-	11	6	6	0	8.4	3.1	0.91	11.90	12.81	75.1
C	Installs k4	11	6	6	1	70.0	23.6	14.04	3.89	17.93	105.2
D	$h_{i,s}$	11	6	6	0	70.0	25.3	10.37	3.89	14.26	83.6
E	$kup_{k,i}$	11	7	7	0	70.0	77.1	14.16	3.89	18.05	105.9
F	-20% e_s	11	6	6	0	70.0	24.5	13.78	3.89	17.67	103.6
G	+20% e_s	11	6	6	0	70.0	24.5	12.54	3.89	16.43	96.4
H	-20% cda_s (S1 e S2)	11	6	6	0	70.0	24.5	13.17	3.34	16.51	96.8
I	+20% cda_s (S1 e S2)	11	6	6	0	70.0	24.5	13.17	4.42	17.58	103.1
J	-20% cda_s (MR1 e MR2)	11	6	6	0	70.0	24.5	11.67	3.89	15.56	91.3
K	+20% cda_s (MR1 e MR2)	11	6	6	0	70.0	24.5	14.68	3.89	18.57	108.9
L*	-20% e_s	11	6	6	0	6.2	2.3	0.74	12.14	12.88	75.5
M*	+20% e_s	11	6	6	0	10.3	3.8	1.02	11.70	12.72	74.6
N*	-20% cda_s (MR1 e MR2)	11	6	6	0	30.0	11.2	2.64	9.88	12.52	73.4
O*	+20% cda_s (MR1 e MR2)	11	6	6	0	5.3	2.0	0.67	12.25	12.92	75.8
P*	-20% cda_s (S1 e S2)	11	6	6	0	6.0	2.2	0.66	10.65	11.31	66.3
Q*	+20% cda_s (S1 e S2)	11	6	6	0	10.3	3.8	1.12	13.17	14.29	83.8
R*	+40% cda_s (S1 e S2)	11	6	6	0	30.0	11.2	3.17	12.39	15.56	91.3
S*	+60% cda_s (S1 e S2)	11	6	6	0	30.1	11.2	3.17	13.64	16.81	98.6
T*	+80% cda_s (S1 e S2)	11	6	6	0	34.5	12.7	4.32	13.72	18.04	105.8
U*	+100% cda_s (S1 e S2)	11	6	6	0	42.3	15.3	6.31	12.84	19.15	112.3

Based on the detailed analysis of scenarios A to E, it is evident that it is more economically viable to landfill waste than to recycle it, since in the scenarios where the parameter Xrec is assigned a value of 0.7, the minimum mandatory percentage (70%) is recycled, and in scenario B (where there is no obligation) only 8.4% of the waste is recycled. Due to the high capacity of the pre-existing plants, the installation of new sorting or recycling plants was not necessary, except for scenario E, in which the total pre-existing capacity of the network is reduced to 20%, making it necessary to install two processes, a k2 and a k3. Regarding the k4 process, this is only installed in scenario C due to the installation obligation, and even then, it is not used, so that all S10 material produced is sold instead of being sent for HQ recycling. Regarding CDW, even though 70% of the waste corresponds to S2, recycling this material is more expensive economically when compared to S1, so that it is more viable to prioritise concrete recycling.

In the remaining scenarios in which recycling 70% of the waste is mandatory (F to K), the results are consistent with the 20% variations (positive and negative) of the parameters. In all cases 70% of the CDW was recycled, reinforcing the conclusion that it is more expensive to recycle the waste. The parameter that had the biggest impact on the results of these scenarios was the cost of landfilling the waste materials (MR1 and MR2), so that when this parameter is reduced, the total cost is 15.56 M€ (8.7% less than in scenario A), and when it is increased, the cost rises to 18.57 M€ (8.9% more than in scenario A).

Finally, in the sensitivity analysis scenarios where no waste must be recycled (L to U), the results are also consistent with the variations made to the parameters. Of the scenarios in which variations of 20% are made (L to Q), the parameter that most affected the results was again the cost of landfilling, but in these cases, it was of the S1 and S2 materials, and not of the waste materials. In P, the landfilling cost of CDW is reduced by 20%, resulting in a total cost of 11.31 M€ (11.7% less than in scenario B and 33.7% less than in A). In scenario Q the landfilling cost of S1 and S2 increases by 20%, resulting in a total cost of 14.29 M€ (11.6% more than in Scenario B, but 16.2% less than in Scenario A).

6. Conclusions

The model developed allows for the decision making of important factors for an effective CDW management, more specifically regarding the type of process to be installed, its capacity and location, in addition to the flow of materials in the network. The results obtained are directly linked to the input data considered, so the quality of the parameters is essential. The analysis of results elaborated makes it possible to verify the influence that each parameter has on the modelling.

In the case study, it can be concluded that the best option from an economic point of view is to landfill the waste directly, since the costs of sorting and recycling cannot match the low prices paid to landfill CDW. In the scenarios where it is mandatory to recycle at least 70% of the waste in order to meet the EU target, exactly the minimum amount defined is recycled, whereas in the baseline scenario without mandatory recycling, only 8.4% of the waste is processed in the plants, thus allowing the conclusion that the minimisation of costs occurs with the majority of the waste not being recycled.

Regarding CDW, it is concluded that recycling S1 waste (concrete) is more profitable than S2 waste (undifferentiated material), due to the difference that the cost of processing these materials has. This conclusion becomes evident because when the CDW production is divided into 30% of S1 and 70% of S2, all concrete produced is recycled, while part of S2 is processed and another part is destined to landfill. Moreover, when a change is made in the waste production, so that the division is equal between the two materials (50% of S1 and 50% of S2), again all the S1 produced is recycled, while S2 is destined for recycling and landfill, entailing a 16.4% reduction in the total cost.

It can be concluded that the cost of landfilling the materials is a parameter with great influence in the model. As previously mentioned, in the scenario where recycling is not mandatory, only 8.4% of the CDW produced is treated. However, when the price of landfilling waste is increased by 20%, the recycling rate increases to 30%, and when this same cost is doubled (100% increase), the percentage of recycled waste is equal to 42.3%, which corresponds to more than five times the initial recycling percentage.

Regarding the HQ recycling process (k4), which does not exist in AML, it is possible to conclude that it is not economically advantageous to install it, since this process was only installed at the moment when a new equation was added defining that there should be at least one process of this type. Moreover, even with the installation, the process does not receive any material, so that all S10 material (LQ concrete) produced is sold.

Finally, it is concluded that if it depends on the authorised capacity of the AML plants, there is sufficient capacity to sort and recycle all the waste produced. The only case where new processes of incorporated sorting (k2) and LQ recycling(k3) are installed was when the pre-existing capacity was reduced to 20%. With this, the processing cost increased by 1M€ compared to the baseline scenario, but the percentage of recycling capacity used was 77.1%, the highest among all the scenarios analysed.

7. References

AlZaghrini, N., Srour, F. J., & Srour, I. (2019). Using GIS and optimization to manage construction and demolition waste: The case of abandoned quarries in Lebanon. Waste Management, 95, 139-149.
DOI: https://doi.org/10.1016/j.wasman.2019.06.011.
Andrade, A.R., Gomes, M.C., & Duque, J. (2017). New approach for optimization of construction and demolition waste management: Application to the Lisbon metropolitan area. Em: Vaz, A., Almeida, J., Oliveira, J., e Pinto, A. (Editores), Operational Research, APDIO 2017. Springer Proceedings in Mathematics & Statistics, vol. 223. Springer, 1-10.
DOI: https://doi.org/10.1007/978-3-319-71583-4_1
Carrola, A.C. (2017). Gestão de Reciclagem dos Resíduos de Construção e Demolição. Agência Portuguesa do Ambiente (APA).
Coelho, A. (2012). Análise de viabilidade de implantação de centrais de reciclagem de resíduos da construção e demolição em Portugal – Parte III – Análise de viabilidade de uma central de reciclagem. Relatório no âmbito de bolsa de pós-doutoramento. Universidade Técnica de Lisboa, Instituto Superior Técnico.
Correia, M.N., Gomes, M.C., & Duque, J. (2015). Optimization of Construction and Demolition Waste Management: Application to the Lisbon Metropolitan Area. Em: Póvoa, A. e de Miranda J. (Editores), Operations Research and Big Data. Studies in Big Data, vol 15. Springer, 33-40.
DOI: https://doi.org/10.1007/978-3-319-24154-8_5.
Decreto-Lei n° 46/2008, de 12 de março de 2008. Regime de gestão de resíduos de construção e demolição. Lisboa.
Decreto-Lei n° 73/2011, de 17 de junho de 2011. Regime de gestão de resíduos de construção e demolição. Lisboa.
Decreto-Lei n°178/2006, de 5 de setembro de 2006. Regime geral de gestão de resíduos. Lisboa.
Deloitte (2017). Study on Resource Efficient Use of Mixed Wastes, Improving management of construction and demolition waste – Final Report. Prepared for the European Commission, DG ENV.
Eurostat (2020a). Generation of waste by waste category, hazardousness and NACE Rev. 2 activity. Disponível em: https://ec.europa.eu/eurostat (online data code: t_env_wasgt). Acedido a 23 de maio de 2020.
Galan, B., Dosal, E., Andrés, A., & Viguri, J. (2013). Optimisation of the construction and demolition waste management facilities location in Cantabria (Spain) under economical and environmental criteria. Waste and Biomass Valorization, 4(4), 797–808.
DOI: https://doi.org/10.1007/s12649-013-9196-0.
Sáez, P.V., & Osmani, M. (2019). A diagnosis of construction and demolition waste generation and recovery practice in the European Union. Journal of Cleaner Production, 241, 118400.
DOI: https://doi.org/10.1016/j.jclepro.2019.118400.
Wu, H., Zuo, J., Zillante, G., Wang, J., & Yuan, H. (2019). Status quo and future directions of construction and demolition waste research: A critical review. Journal of Cleaner Production, 240, 118163.
DOI: https://doi.org/10.1016/j.jclepro.2019.118163.
Xu, J., Shi, Y., & Zhao, S. (2019). Reverse Logistics Network-Based Multiperiod Optimization for Construction and Demolition Waste Disposal. Journal of Construction Engineering and Management, 145(2), 0418124.
DOI: https://doi.org/10.1061/(ASCE)CO.1943-7862.0001592.