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Improving the Performance of Urban Waste Management Systems in the Context of a Closed-Loop Supply Chain

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Abstract

The saving of non-renewable energies, as well as the reduction of emissions into the environment, are two crucial objectives of industrial production. The recovery of post-consumer products associated with the use of end-of-life products is part of a context of optimization of these objectives. This recovery maximizes the use of resources from end-of-life products in a circular logic while recording the environmental footprint. This study considers a recycling strategy adapted to the need and urgency to reduce greenhouse gas emissions caused by global warming. The proposed model aims to optimize the profits of the circular manufacturing strategies while minimizing operational costs (collection, sorting, recycling), transport, *GHG* emissions and recycling. In this paper, a compromise between the gains of CM and the costs associated with it was studied. The robustness of the designed model was tested using a case study based on real-world scenarios. A sensitivity analysis was carried out to study the impact of the emission cost on the overall objective, considering the two options currently offered to industries. The obtained results support companies to take the ecological aspect into account and integrate sustainable development into their strategic axes for their logistics supply chains.

Keywords

Waste Management, Closed-Loop Supply Chain, End-of-Life Products, Circular Economy, *GHG*, Sensitivity Analysis

1. Introduction

Today's current global production and consumption patterns are unsustainable. Nearly 90 billion tons of natural resources are extracted each year to meet the needs of society and it is expected to double by 2050. That same year, the world's population is expected to reach 9.7 billion and the demand for finite resources will reach 400% of the Earth's total capacity Goueland Guimbard. [1]. It is therefore, time to think about implementing more sustainable practices for tomorrow by taking advantage of the resources that already exist today. These practices are part of a concept referred to as the Circular Economy (*CE*). Its goal is to produce goods and services while strongly limiting the waste of resources. In Canada, the concept of circular economy has advantages from different points of view. Indeed, the country has prospered for centuries due to the abundance of its resources. Currently, these natural resources constitute 17% of Canada's Gross Domestic Product *GDP* and support 1.75 million jobs. In addition to providing stability and a sense of physical and mental well-being to the population, this job creation promotes the productivity and profitability of companies Bonet *et al.* [2]. In fact, it is about 236 billion dollars that fuel the Canadian economy.

In addition to the social and economic benefits mentioned above, the circular economy is intended to be restorative and regenerative. Indeed, apart from aiming to double job creation and increase gross domestic product, it is committed to reducing *GHG* emissions significantly while reducing pressure on resources and supply costs by 70% Steffen *et al.* [3]. Circular economy practices, including residual materials management (*RMM*), are carried out mainly in cities which are a hotspot for resource cycles since they consume up to 80% of the world's natural resources and produce 50% of the world's waste and 75% of greenhouse gas emissions Amrani *et al.* [4]. In this work, we are interested in the waste that consumers produce in their homes. This household waste can be considered as end-of-life (*EOL*) products containing residual value just waiting to be exploited by Alamerew and Brissaud. [5]. Hence, their efficient management would reduce environmental pollution, create new raw materials, and generate profit while creating jobs that allow people to live with dignity in society. To achieve the most optimal urbane waste management, we will first carry out a review of the existing literature dealing with the subject. Then, we will extract the problem of this research.

This article is organized as follows: In introduction, the literature review and the research problem are presented. Section 1 presents the proposed approach. The optimization model and sensibility analysis are presented in Section 2. Finally, the paper is concluded in Section 3.

The circular economy is meant to be restorative and regenerative in relation to the environmental issues of the industry. Indeed, in addition to the objective of doubling job creation and increasing gross domestic product, it is committed to reducing greenhouse gas emissions by 70% while reducing pressure on resources and supply costs Steffen *et al.* [3]. Circular economy practices, including residual materials management (*RMM*), are carried out mainly in cities which are a hotspot for resource cycles since they consume up to 80% of the world's natural resources and produce 50% of the world's waste and 75% of greenhouse gas emissions Amrani *et al.* [4]. This literature discusses existing work and studies on waste valorization in Section 1.1, ecological waste management in Section 1.2, economic challenges on waste management in Section 1.3, and current urban waste practices discussed in Section 1.4.

1.1. Valorization of Waste and Creation of Raw Materials

The high consumption of natural resources leads to a decrease in the latter. Most of these resources, like petroleum-based plastics, often must be destroyed (e.g., incinerated) when they are deemed unrecoverable. On the other hand, certain ores necessary for high-tech production are becoming increasingly rare, posing problems at other levels. As these are controlled by economically competing countries, replenishment can be a problem in the event of a shortage. Therefore, the idea of reusing material from waste as raw material in manufacturing processes could eventually solve such issues. Safaei *et al.* [6], Cariou *et al.* [7] and McDonald *et al.* [8] argue that recycling paper and cardboard is one of the best secondary materials in the world, constituting a real source of usable raw materials. Their work presents a new framework to support paperboard supply chain managers in designing an optimal closed-loop paperboard supply chain (CLSC) that considers a mix of internal and external flows for the recycling network.

Such a chain would be much more efficient thanks to the use of the Internet of Things (Zuo *et al.* [9], Misra *et al.* [10], Al-Masri *et al.* [11], and Ferrari *et al.* [12]). Similarly, Miao *et al.* [13] propose a new recycling mode based on the "$O2O$" classification (online to offline) capable of integrating upstream and downstream resources on a network platform named "$O2O$ waste recycling platform" where consumers log in, register, and complete the recycling process through online submissions by following a defined user guide. In a subsequent step, green recyclers receive instructions that allow them to contact the consumer for a collection appointment, thus contributing to the development of a circular model integrating "resources-products-waste renewable resources" where raw materials are regenerated.

1.2. Ecological Waste Management

There are many ecological problems caused by the disposal of end-of-life products. Indeed, most do not degrade alone in nature and others can release elements that until then did not exist in the environment, thus, causing irreversible damage to the health of humans and their environment. Certain quantities have a strong impact on the ecosystem but also on the living conditions of the populations located near the treatment areas. Although manufacturers are sensitive to these dangers, their points of view differ as to the solutions to be adopted. Ghahremani *et al.* [14] believe that a closed-loop system is feasible and have developed a bi-objective, multi-period, multi-product, closed-loop supply chain network taking into account environmental considerations, discounts and uncertainties while Samuel *et al.* [15] proposed a deterministic mathematical model and its robust variant in which they studied the possibility of adding pre-sorting in the *CLSC* network, which would generate costs that are generally lower than those incurred in the subsequent stages of processing. These pre-sorting centers would separate poor-quality products at the beginning of the reverse logistics cycle, thus reducing transport costs and many others. Among these, an emerging cost of emissions, called the green cost, is beginning to gain momentum. This is involved in the management of a green supply chain taking into account greenhouse gas emissions in the total costs of logistics in particular by proposing a model which not only takes into account the characteristics and performance of an entity (vehicles of manufacturers) by calculating the carbon dioxide emissions for a certain type (e.g. a truck), but also the emissions linked to transport, to the operation of the installations in terms of energy consumption, transport of employees, paper consumption and computer use (Baland Satoglu [16]). Others have tried to minimize the environmental impact (in the case of transport fleets) by building a green supply chain model integrating forward and reverse queuing logistics to optimize transport and waiting time. of the network (of these fleets) to reduce environmental impacts (Mohtashami *et al.* [17]).

1.3. Economic Challenge of Waste Management

The high consumption of natural resources also leads to a decrease in its supply and therefore an increase in prices in parallel with the high rate of demand and although manufacturers are aware of the need to adopt a production that is more respectful of the environment, they nonetheless remain dependent on the economic profitability of their businesses Jiang *et al.* [18] presented a general closed-loop supply chain network including various recovery options and formulated a mixed-integer multi-objective linear programming model considering the firm's profit as well as its service level. In addition, waste generates costs, regardless of its origin (transformation process or the obligation to treat the production at the end of its life). It is therefore essential to consider adopting good waste management to optimize the costs associated with it. Aware of this, Ghahremani-Nahr *et al.* [14] designed a mathematical model of a multi-period multi-echelon closed-loop supply chain under uncertainty whose objective is to determine the quantities of products and raw materials transported between entities in the chain during each period by minimizing the total logistics cost which includes fixed, opening and closing costs, transportation costs between facilities, inventory holding costs, operation in all facilities (production costs, distribution costs, collection costs, repair costs, recovery/decomposition costs, disposal costs) and shortage costs.

Finally, the need to justify the use of such management encourages researchers to compare sales revenues with the various costs of the logistics adopted. This example was followed by Scheller *et al.* [19] who, in the case of lithium-ion batteries, proposed models for optimizing production and recycling planning that generate a maximum revenue-cost margin.

1.4. Urban Society and Waste

The design of a model stipulates that one must first estimate the value of the chosen criteria before being able to assess whether the constraints are respected. Among these criteria is the international standard for guidance on social responsibility (*ISO* 26000) for the identification of social criteria around seven major themes and five categories of social factors. The major themes include organizational governance, human rights, work practices, environment, fair operating practices, consumer issues, community involvement and development considered by Bal and Satoglu. [16]. The categories include demand satisfaction, resource equity, development opportunities employment, regional development, level of safety on site, level of access to medical facilities. Such categories are described as the local development objective (Anvari and Turkey [20]). And then accompanied by maintaining the number of workers at a certain level for an operating facility as a social goal. In this work, we are interested in the waste that the consumer produces in his home. These household wastes are end-of-life (*EOL*) products containing residual value just waiting to be exploited (Alamerew and Brissaud [5]). Thus, their good management would reduce environmental pollution, create new raw materials, and generate profit while creating jobs that allow people to live with dignity in society. To do this, we will first carry out a synthesis of the literature reviewed dealing with the subject. Then, we will extract the problem of this research.

A significant amount of sustainable supply chain research has been conducted considering various sustainability indicators in decision-making and operations management. Compared to extensive research on environmental aspects and especially economic issues, social and resource supply aspects are often overlooked in the urban waste management (*UWM)* literature. In the following, we summarize recent work by looking at different aspects of the problem (raw materials, ecological aspect, economic and social aspect). **Table 1** summarizes the recent literature review in the field of waste management; it seems clear that the ecological, social, economic and resource aspects, although they are strongly linked and sometimes mutually impacted, do not appear together in the studies carried out to date. The objective of this work is to study, model and optimize the impact on *UWM* of these four axes.

1.5. Issues and Objectives

As shown in the previous table, the different aspects (ecological, economic, social and resources) have been treated separately in the literature. No study has, to date, investigated the possibility of monitoring the impact of urban waste recovery on society, the environment, the availability of resources and the economy. However, the researchers did not rule out the idea that there is a link between them and strongly encouraged their joint integration in future decision models to be proposed. Thus, the research question to answer is: how to manage domestic waste to create new resources, protect the environment, and reduce the

Table 1. Summary of the literature review.

Paper	Aspect			
	Ecologic	Economic	Social	Resources
Gouel and Guimbard [1]	✓		✓	
Bonet *et al.* [2]			✓	✓
Steffen *et al.* [3]	✓	✓		
Amrani *et al.* [4]	✓		✓	
Alamerew and Brissaud [5]	✓			✓
Safaei *et al.* [6]		✓		✓
Cariou *et al.* [7]		✓		✓
McDonald *et al.* [8]	✓			✓
Zuo *et al.* [9]	✓	✓	✓	
Misra *et al.* [10]	✓		✓	
Al-Masri *et al.* [11]		✓		✓
Ferrari *et al.* [12]	✓	✓		
Miao *et al.* [13]	✓			✓
Ghahremani-Nahr *et al.* [14]	✓	✓		
Samuel *et al.* [15]	✓	✓		
Bal and Satoglu [16]	✓	✓	✓	
Mohtashami *et al.* [17]	✓			✓
Jiang *et al.* [18]		✓	✓	
Scheller *et al.* [19]	✓	✓		
Anvari and Turkay [20]	✓	✓	✓	
Proposed research	✓	✓	✓	✓

unemployment rate and all while making a profit?

This study will deal more in-depth with the issue of household waste, the material, social, ecological, and economic objectives to be achieved by developing the model and the methodology used to achieve it. It is therefore, necessary to identify the environmental and economic indicators, to understand the current problem of urban waste and the ideal scenario to be achieved. Finally, it would be relevant to look at a particular case to verify how such management is usually exercised to test performance and validate the logic and feasibility of the model developed. A sensitivity analysis should support the decisions proposed by the model. This one, although elaborated for a local territory, appears appropriate in the current context to solve this kind of problem on other scales.

2. Proposed Approach

This study aims at designing and presenting a model based on the ecological, economic, social and resource axes to respond to the problem mentioned above and propose an alternative to conventional *UWM* which would help decision makers to better choose between the possible alternatives (impose a pre-sorting or not). The proposed approach consists of seven steps S1 to S7) related to the following stages shown in Figure 1.

Stage 1. Modeling and optimizing the *UWM* (case with vs. without pre-sorting). The objective is to prove the economic, social, and ecological efficiency of the model by comparing the total costs generated by the current *UWM* with those of the proposed method in which various costs related to management, the environment, and the conservation of resources are considered (S1 to S3).

Stage 2. Anticipate possible decisions by governments decreeing an increase in dissipation penalties by implementing the model and making a sensitivity analysis through increasing scenarios which aims to determine the impact that such decisions can have on the cost of issuance and therefore, on the overall objective (S5 to S7).

The 7 steps considered in this research are:

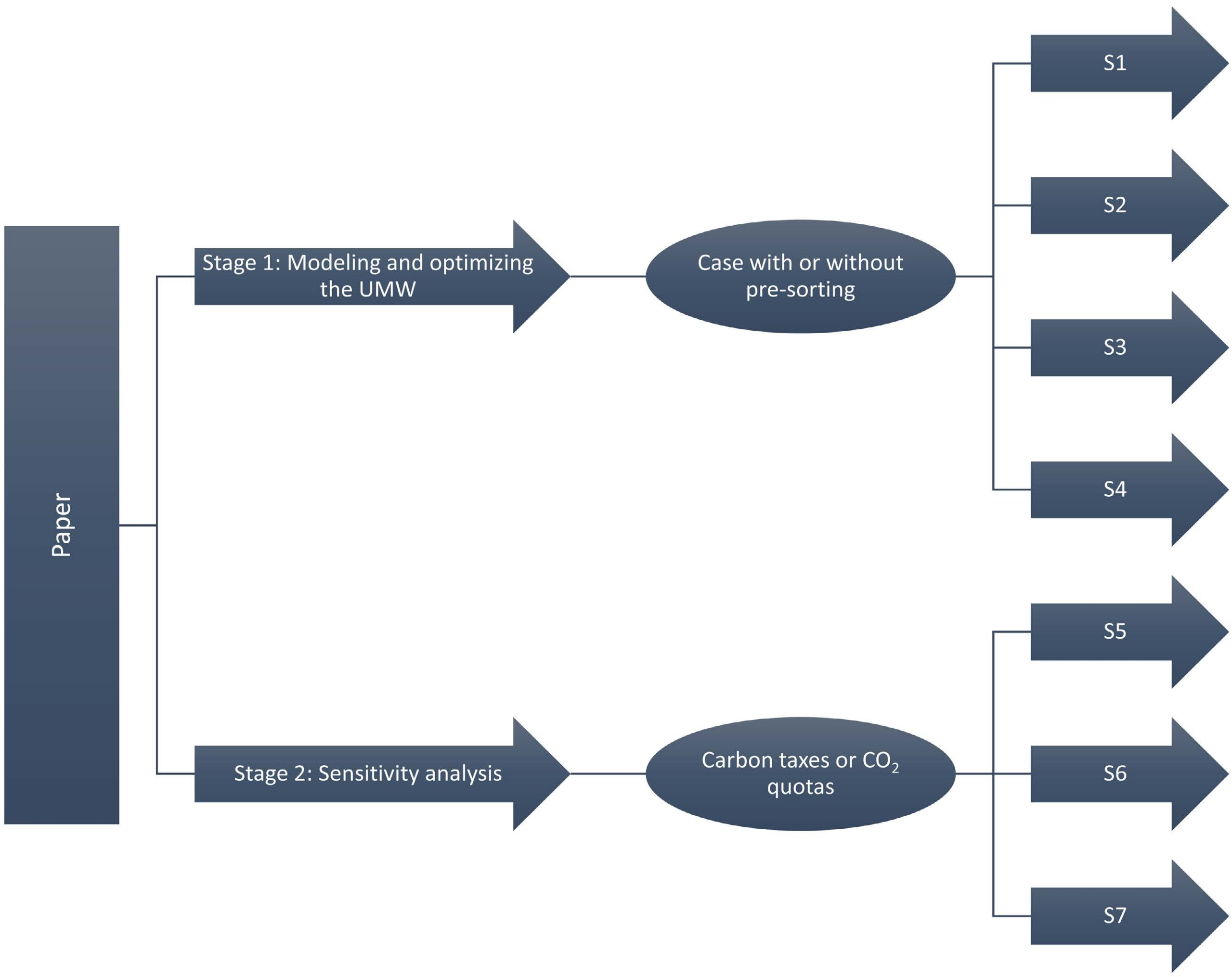


Figure 1. Proposed approach.

- S1: Presenting the reference case.
- S2: Transformation of the model by including a first selective sorting at the consumer's home (the proposed case).
- S3: Formulation of the optimization problem.
- S4: Implementation of the two models in the basic case and construction of the corresponding code.
- S5: Carry out a sensitivity analysis involving new *GHG* emission policies to choose among the recent strategies proposed by *COP*26.
- S6: Extend the model by including the new *COP*26 constraints and objectives.
- S7: Numeral application and discussion of the results.

The developments associated with these steps constitute the content of the following section which presents the proposed mathematical model as well as the obtained results.

3. Modeling and Optimizing the UWM (Case with vs. without Pre-Sorting)

The objective of this part is to design and develop a compact model capable of managing municipal waste (cardboard, plastic, metal, glass, etc.) while considering their impact on the preservation of resources, ecological, economic, environmental, and social. The literature reviewed allowed us to separately identify the different costs and parameters related to the axes studied. We propose the study of a reference case taken from the literature and from which we will build a first model corresponding to the case of municipal waste management without the possibility of pre-sorting at home Bal and Satoglu. [16]. To validate this, we will incorporate costs omitted from the base case, such as inventory costs, and then forecast the demand for recycled materials for the next 12 months. Then, we will improve the performance of the model designed from the reference case with, this time, the possibility of carrying out a first selective sorting directly in the consumer's household.

Step 1. The model designed in the studied article encompasses four objectives determined according to the minimization of costs, the reduction of environmental effects, the balance of manpower and equal objectives. Thus, **Figure 2** corresponds to the block diagram illustrating the reference case from which we drew our inspiration.

Storage costs are ignored, and the income generated by the satisfaction of demand (often stochastic), although cited, is not considered in the proposed model. Adding inventory and shortage costs to the model in **Figure 1** in a municipal waste management context will allow us to obtain the model corresponding to the case without selective sorting at home illustrated in **Figure 3**. The logistics network based on the reference case and considering a *UWM* without pre-sorting is illustrated in **Figure 3**.

Figure 3 is inspired by the reference case presented in Bal and Satoglu [16] to

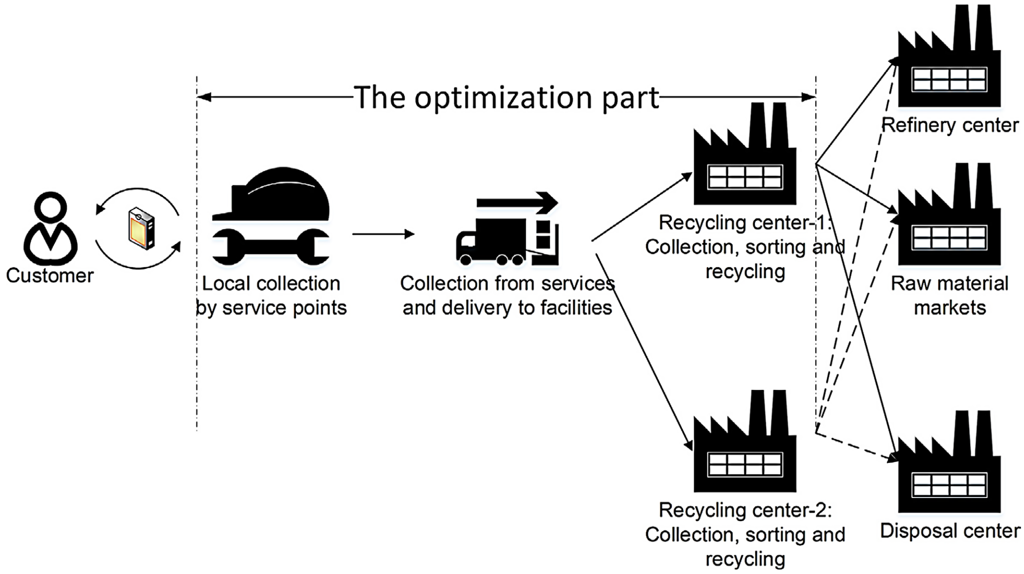


Figure 2. Reverse logistics network (from [16]).

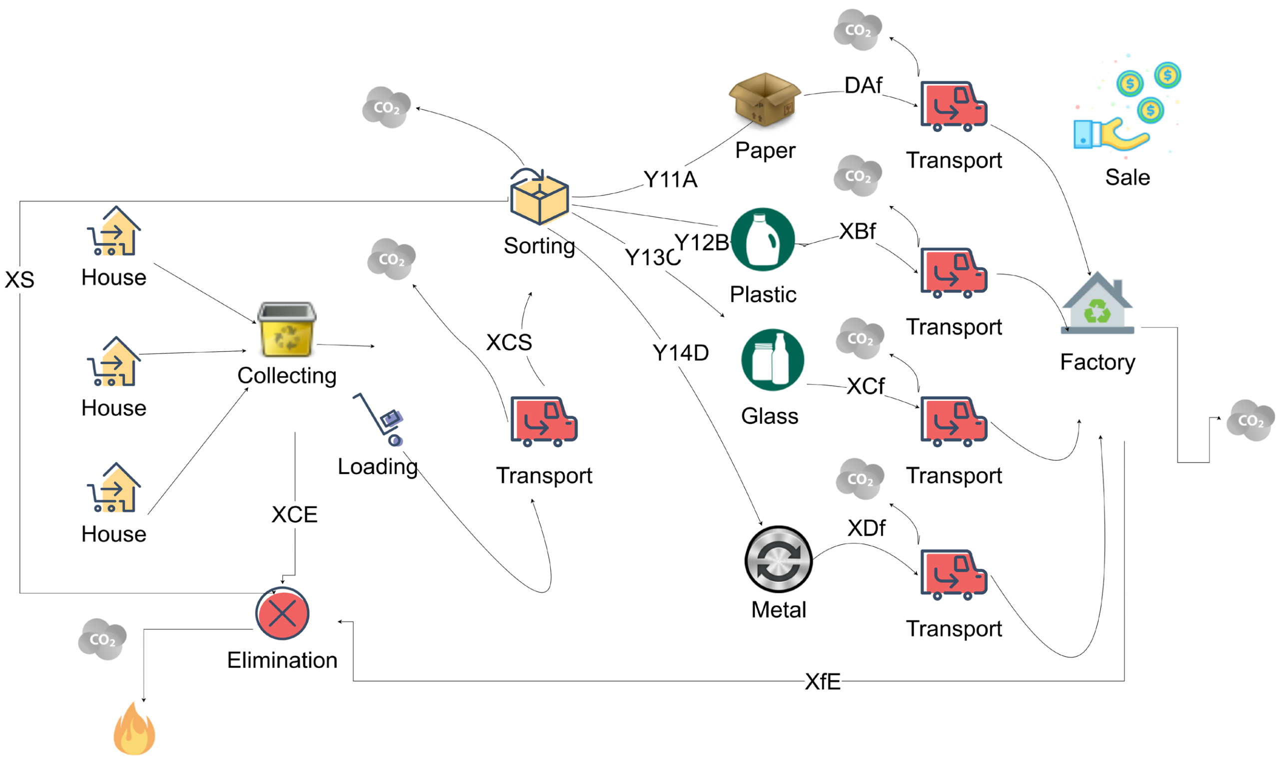


Figure 3. Model inspired by the reference case (without pre-sorting).

model the logistics of municipal waste management at the scale of a city like Montreal (which can extend over a province like Quebec) with the goal of maximizing profits corresponding to the difference between sales revenue and associated costs. This model (case without selective sorting) will consider the stochastic aspect of the demand which makes it possible to guarantee the supply. It will also consider more than one type of product and will set up an overstock management policy.

Step 2. In this part, we carry out modeling of the logistic network for the activity of household waste management in the case where a first sorting is carried out at the consumer's house. According to Figure 3, waste from each household (h) is collected in the different sectors of Montreal, at the curb, then transferred to sorting centers where manual and/or automatic sorting is carried out to design mono-materials (cardboard, plastic, metal, glass, etc.). Depending on the contamination level of the material, the next decision is to send the waste to recycling or disposal centers. Then recycling centers also have the option of recycling the quantities received or sending them to disposal centers. It should also be noted that the rate of materials to be recycled is a fixed parameter of the proposed model. This percentage is the objective of the annual *UWM* targeted by the various government awareness campaigns and implied in the proposed model. The diagram in Figure 4 represents the logistics adopted for such a *UWM*.

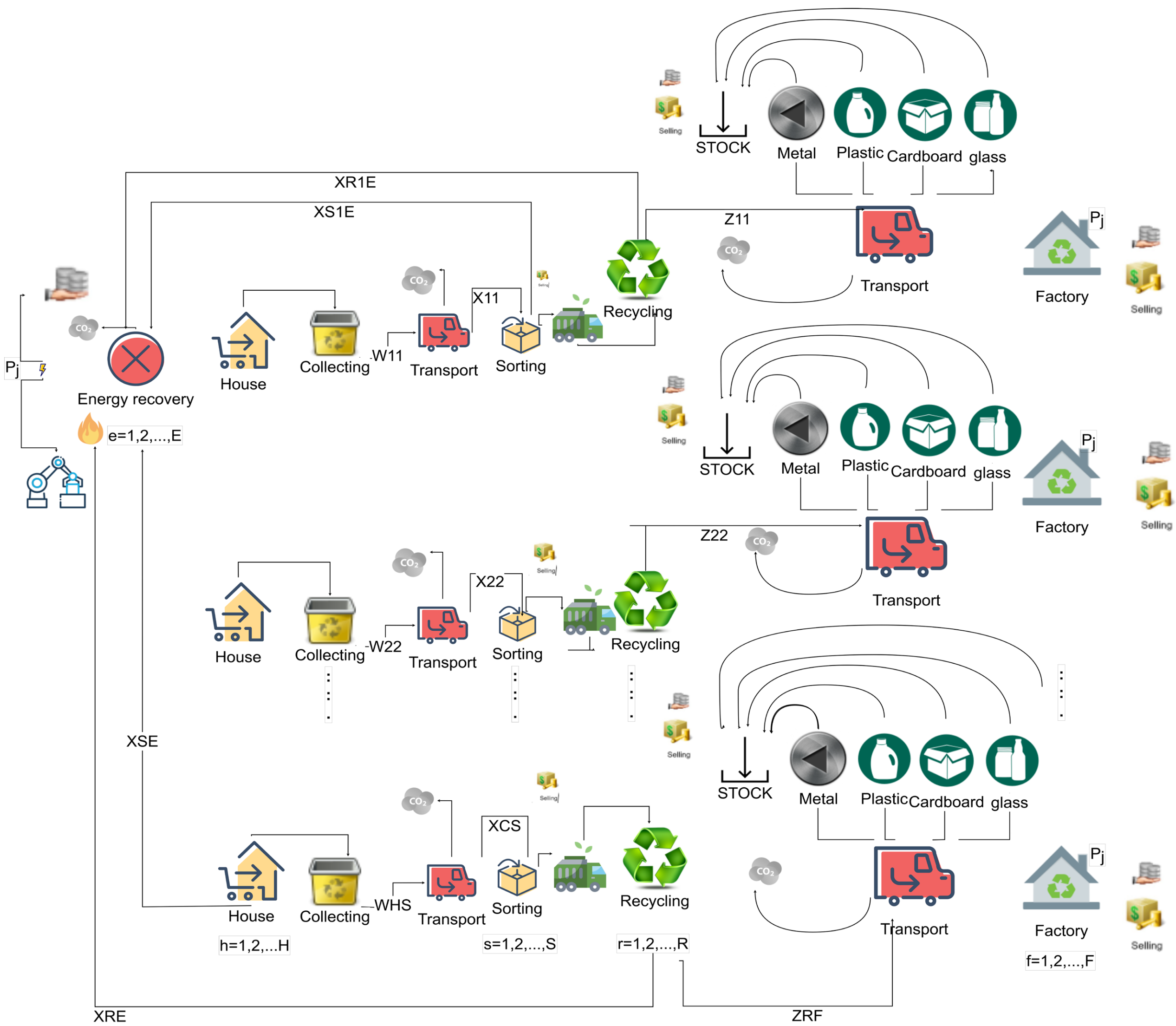


Figure 4. Diagram of the proposed urban waste management model (with selective sorting).

Nodes from left to right, represent consumer households $h \in \{1, 2, \cdots, H\}$ as well as waste bins $c \in \{1, 2, \cdots, C\}$ linked by arcs illustrating material flow Xhs collected at this level. Once loaded into trucks, these quantities Xhs will be transported to sorting centers $s \in \{1, 2, \cdots, S\}$, then to recycling $r \in \{1, 2, \cdots, R\}$ from which will result in a characterization and classification of materials: paper, plastic (*PET*, *HDPE*, *PVC*, *LDPE*, *PP*, *PS*), glass and metal. This classification will identify the right customer (the highest bidder) for the right product. Such a decision is represented by the binary variable Yf where $f \in \{1, 2, \cdots, F\}$ represents a potential customer. This will be activated (will take the value 1) if the quantities of materials transported in the truck will be sold to the customer $f \in F$ (and 0, otherwise). The unsold sorted units will be stored to prevent a possible shortage of materials in the future or will be sold in bundles to the various recycling centers. At this level, other profits will be considered. As for materials that have been contaminated or whose life cycle turns out to be shorter than expected, the energy recovery process will allow them to act as an equally essential element in the recycling chain because this will release enough heat and energy to power the machinery.

Step 3. This step includes a mathematical formulation of the problem to be optimized by considering the two cases (with or without selective sorting). It is a compact mixed linear program including integer variables and binary variables (*MILP*) that can be implemented and run with *LINGO* software. The objective will be to optimize the flow of materials to be transported to customers while minimizing the main costs linked to their logistics process: the operational cost of treatment, transport (which is proportional to the distance traveled and represented the purchase and fuel consumption), as well as the green cost (vehicle greenhouse gas emissions). The optimum quantities, as well as the designation of the centers to which the waste is sent will be determined by the model presented below.

The sets, the parameters, and the decision variables on which the model is based are the following.

Sets.

H: All homes.

S: All sorting centers.

A: All recycling centers.

E: All elimination centers.

F: All customer factories.

Parameters.

C_s: Sorting center capacity s.

C_e: Disposal center capacity e.

P_i: Unit sale price of recycled product i (\$/t).

a: Unit cost of treatment-sorting center (\$\t).

η: Unit disposal cost (\$\t).

u: Unit collection cost (\$\t).

θ: Unit cost of GHG emissions ($).

m: Recycling unit cost ($/t).

c: Unit transport cost ($/t-km).

f: GHG emission factor (t Co2 eq/km).

d_s: Distance between h and center s (km).

d_{sr}: Distance between center s and center r (km).

d_{rf}: Distance between center r and factory f (km).

ρ: Storage unit cost ($\t).

Ω: Percentage of waste to be recovered (%).

D_{fi}: Request from customer f for product i (t).

k_r: Amount of waste available in recycling center r (t).

Q: Quantity of waste (t) requiring a threshold of 70% of employees (workforce).

Decision variables.

X_s: Amount of waste sent from h to center s (t).

X_{sr}: Amount of waste sent from s to r center r (t).

X_{se}: Amount of waste sent from s to center e (t).

X_{re}: Amount of waste sent from r to center e (t).

X_{Arf}: Amount of paper waste i sent from r to plant f (t).

X_{Brf}: Quantity of plastic waste i sent from r to plant f (t).

X_{Crf}: Amount of glass waste i sent from r to plant f (t).

X_{Drf}: Amount of metal waste i sent from r to plant f (t).

X_{rti}: Amount of i waste stored in the g center r (t).

Y_{fi}: Factory selection (1 if factory f is a customer of product i, 0 otherwise}.

Objective function

$$
\begin{aligned}
MAX = & \sum_{f\in F}\sum_{r\in R}\left(P_A x_{Arf} y_f + P_B x_{Brf} y_f + P_C x_{Crf} y_f + P_D x_{Drf} y_f\right) \\
& - c\left(\sum_{s\in S}\sum_{h\in H} d_{hs} + \sum_{e\in E}\sum_{s\in S} d_{se} + \sum_{r\in R}\sum_{s\in S} d_{sr} + \sum_{e\in E}\sum_{r\in R} d_{re} + \sum_{f\in F}\sum_{r\in R} d_{rf}\right) \\
& - u\left(\sum_{s\in S}\sum_{h\in H} x_{hs}\right) - a\left(\sum_{r\in R}\sum_{s\in S} x_{sr}\right) - m\left(\sum_{f\in F}\sum_{r\in R} x_{rf}\right) - \eta\left(\sum_{e\in E}\sum_{s\in S} x_{se}\right. \\
& \left. + \sum_{e\in E}\sum_{r\in R} x_{re}\right) - \theta f\left(\sum_{s\in S}\sum_{h\in H} d_{hs} + \sum_{r\in R}\sum_{s\in S} d_{sr} + \sum_{f\in F}\sum_{r\in R} d_{rf} + \sum_{e\in E}\sum_{s\in S} d_{se}\right. \\
& \left. + \sum_{e\in E}\sum_{r\in R} d_{re}\right) - \rho \sum_{f\in F}\sum_{r\in R}\Big(\left(x_{Arf} - D_{Af} + k_{Ar}\right) + \left(x_{Brf} - D_{Bf} + k_{Br}\right) \\
& + \left(x_{Crf} - D_{Cf} + k_{Cr}\right) + \left(x_{Drf} - D_{Df} + k_{Dr}\right)\Big)
\end{aligned} \tag{1}
$$

Constraints.

Sorting center capacity constraint:

$$\sum_{s\in S}\sum_{h\in H} x_{hs} \le c_s \quad \forall s \in S \tag{2}$$

Capacity constraint of recycling centers:

$$\sum_{r\in R}\sum_{s\in S} x_{sr} \le c_r \quad \forall r \in R \tag{3}$$

Capacity constraint of disposal centers:

$$\sum_{e\in E}\sum_{s\in S} x_{se} + \sum_{e\in E}\sum_{r\in R} x_{re} \le c_e \quad \forall e \in E \tag{4}$$

Flow conservation constraints:

$$\sum_{s\in S}\sum_{h\in H} x_{hs} = \sum_{r\in R}\sum_{s\in S} x_{sr} + \sum_{e\in E}\sum_{s\in S} x_{se} \quad \forall s \in S \tag{5}$$

$$\sum_{r\in R}\sum_{s\in S} x_{sr} + \sum_{r\in R} x_r = \sum_{f\in F}\sum_{r\in R} x_{rf} + \sum_{e\in E}\sum_{r\in R} x_{re} + \sum_{r\in R} k_r \quad \forall r \in R$$

Demand Fulfillment Constraint:

$$\sum_{r\in R}\left(x_{Mr} + k_{Mr}\right) + \sum_{f\in F}\sum_{r\in R} x_{rMf} = D_{iMf} \tag{6}$$

$$\forall f \in F, \forall M \in \{A, B, C, D\}, \forall i \in \{jan, fev, \cdots, dec\}$$

Employment constraint:

$$\sum_{s\in S}\sum_{h\in H} x_{hs} \ge \Omega Q \tag{7}$$

Constraint of non-negativity

$$x_{ijk} \ge 0 \quad \forall (i, j, k) \tag{8}$$

Step 4.

In this part, we will test the robustness of the model in a simple case where we consider a basic structure inspired by **Figure 3** and containing an element of each set (recycled material: paper, a building, a sorting center, a recycling center, and a customer factory). To control the stochastic aspect of demand, we will make forecasts for the next 12 months using the *ARIMA* method based on *R language*. **Table 2** represents the recent demands for paper constituting the time series on which the forecasts are based.

The *R language* instructions Demand <- ts (data = Y, start = 1, end = c(9), frequency = 3) and Arima (Demand) allow to observe the crooks for the year 2021 which are given by **Table 3**.

The resolution was made using *LINGO* and the results are presented in **Table 4**.

The results obtained in **Table 4** are represented in **Figure 5** which shows the evolution of the stock, the environmental cost, and the monthly demand according to the decisions to be made.

The target indicated for each case in **Figure 5** is the result of the difference between the sales revenue and the various associated costs whose value is presented in **Table 5** and **Table 6** where:

Table 2. Quantities (tons) of paper sold in 2020.

Month\Demand	Jan	Feb	Mar	Apr	May	Juin
	10,600	13,400	18,300	17,200	11,600	10,600
	Jul	Aug	Sept	Oct	Nov	Dec
	14,200	11,100	14,900	16,600	12,100	16,300

Table 3. Demand forecast for 2021.

Month	Dem (tons)	Unit Price
Jan	12,756	
Feb	12,203	
Mar	13,626	
Apr	13,552	
May	12,473	
Jun	13,105	67$
Jul	13,207	
Aug	13,126	
Sept	12,855	
Oct	13,019	
Nov	13,471	
Dec	12,580	

Table 4. Case study results. A. Case without pre-sorting. B. Case with pre-sorting.

Case A			Case B		
Month	Q_Month/t	Rev_vente/$	Month	Q_Month/t	Rev_vente/$
Jan	13,776	922,992	Jan	45,604	3,055,468
Feb	13,903	931,501	Feb	51,063	3,421,221
Mar	13,324	922,708	Mar	42,915	2,875,305
Apr	13,856	928,352	Apr	40,370	2,704,790
May	13,746	920,982	May	41,209	2,761,003
Juin	13,700	917,900	Juin	48,661	3,260,287
Jul	13,804	924,868	Jul	40,205	2,693,735
Aug	13,788	923,796	Aug	51,134	3,425,978
Sept	13,915	932,305	Sept	39,723	2,661,441
Oct	14,008	938,536	Oct	40,277	2,698,559
Nov	13,880	929,960	Nov	53,947	3,614,449
Dec	13,704	918,168	Dec	46,053	3,085,551

Table 5. Result of case A (without pre-sorting).

CASE A: Objective = −343735.00$							
C_Trs/$	C_Em/$	C_Op/$	C_Elim	C_St	Q_Recup/t	Q-Elim	Rev_sell/$
289,118	116,835	8,902,739	2,064,526	52583.4	424,440	206,452	11,082,068

Table 6. Result of case B (with pre-sorting).

CAS B: Objectif = 490202.00$							
C_Trs/$	C_Em/$	C_Op/$	C_Elim	C_St	Q_Recup/t	Q-Elim	Rev_sell/$
327240.84	134,730	12,570,700	0	420687.16	628,800	0	13,943,560

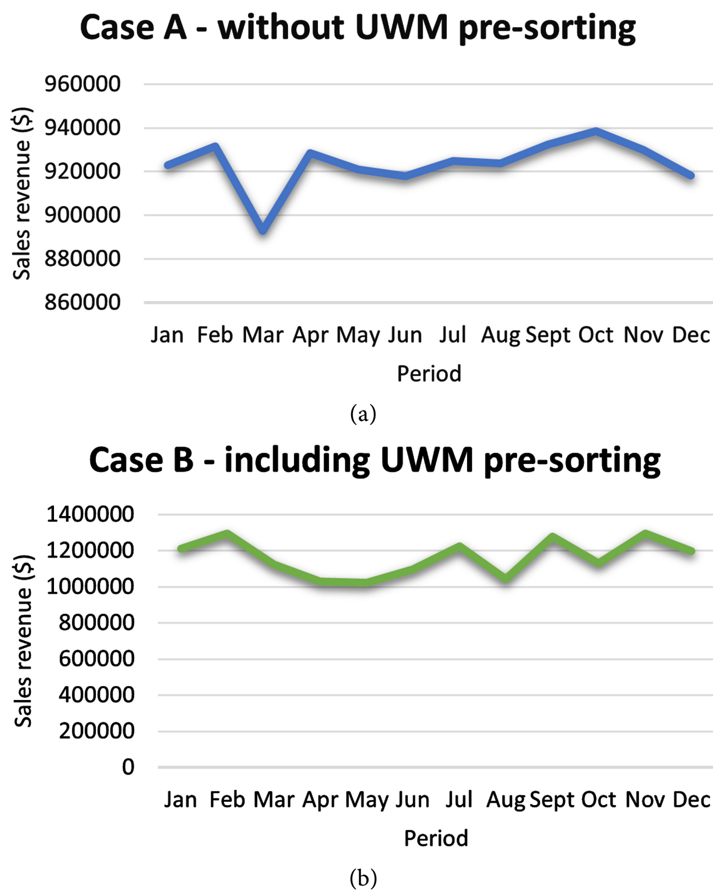


Figure 5. Result of case study (a). Case without pre-sorting. (b). Case with pre-sorting.

C_Trs: is the transport cost ($).

C_Em: is the CO_2 emission cost ($).

C_Op: is the operational cost ($).

C_Elim: is the elimination cos ($).

Q_Recup: is the amount of waste collected (ton).

Q_Elim: is the amount of waste eliminated (ton).

Rev_sell: is the sales revenue ($).

According to Figure 5 as well as Table 5 and Table 6, in case B (with selective sorting), the income from the sale is worth $13,943,560, while in the absence of pre-sorting (case A), it is worth $11,082,068. This is since municipal waste bins are less contaminated when they are pre-sorted by consumers (case B) and therefore, the quantity to be recovered for recycling purposes is greater and generates a higher income than in the case where no pre-sorting is performed (case A). The operational cost of collection, sorting, recycling and disposal amounts to $12,570,700 in the presence of pre-sorting (case B) and to $8902739.14 when there is no pre-sorting (case A). This is since the quantities of waste recovered and requiring treatment on the sites are higher in the case with selective sorting (case B) while in case A, the contaminated waste no longer having any residual value does not require any treatment but will increase disposal cost. The cost of *GHG* emissions is only worth $134,730 in the presence of selective sorting and $116835.77 in the case without pre-sorting, to which we add an elimination cost of up to $2,064,526. This emission cost (better known as the *Green Cost*) seems negligible compared to the operational cost. This is because the green strategy imposed by governments is emerging and gradually taking hold to let decision-makers embrace green costs in their direct and return supply chains. Given this progression to become, in what follows, we will study the impact of the progressive variation of this green cost on the overall objective through a sensitivity analysis.

Step 5. The interpretation of the cost and greenhouse gas emission limits plays a role in this sensitivity analysis. The goal here is to anticipate possible decisions by governments decreeing an increase in dissipation penalties. Through increasing scenarios, this analysis aims to determine the impact that such decisions can have on the overall objective. Canadian ministers set the goal in March 2016: a 30 percent reduction below 2005 greenhouse gas (*GHG*) emission levels by 2030. They agreed to the pricing of carbon as a policy strategy for reducing *GHG* emissions.

Two carbon pricing options have gained traction:

- A carbon tax, levied on the volume of emissions (per ton),
- A cap and trade system that sets a limit on emissions and requires emitters to buy allowances under a fixed offer.

The federal government has proposed that the price per ton start at $10 in 2018 and rise to $50 per ton in 2022. In this part, we study the impact of the two strategies on the total cost by performing an analysis of sensitivity. To do this, we first vary the ceiling limit provided in the text of the Canada's legislation until the objective coveted by the government for 2030 is reached. Then, we vary the allowances purchase price defined above as one of the two options and which grows annually (from $10-$50 between 2018 and 2022). The Copenhagen accord stipulates that the value of CO_2 emissions from heavy-duty engines cannot exceed the CO_2 standard of 627 g/BHP-Hour during their useful life. This standard is defined according to the maximum quantity of emissions according to distance in the case of light vehicles (less than 3855 kg) or according to brake horsepower per hour (bhp/h) in the case of heavy vehicles. The following step should allow us to identify the new parameters to include in the model.

Step 6.

In this step, we extend the flexibility of the model presented in stage 1, by adding the formulas taken from the new *GHG* emission policies cited in step 5 of stage 2. Thus, we assume that:

Nr: Heavy-Duty Engine CO_2 Emission Standard (627 g/BHP-hr).

V: Speed of class 8 heavy vehicle (105 km/h).

E: The emission of CO_2 per class 8 heavy vehicle is 99.7 g CO_2 e/km.

Tx: Carbon tax ($/ton).

BHP: Heavy vehicle brake power.

Qta: Quota purchase price (from \$10-\$50 between 2018 and 2022).

T: Maximum number of vehicles.

In this study, we design heavy-duty vehicles specialized in the collection and transport of urban waste whose *X*15 *Volvo-series* 505 - 605 *hp*, 1850 - 2050 *lb-ft* engines are equipped with a brake power that can reach 600 hp. In the case of the Quebec-California market, each unit (equivalent to one metric ton of *CO*2) has a floor price in CAD that increases by 5% per year.

According to the data extracted from the context studied, the vehicles used in this study must satisfy Equation (9).

$$\frac{E \times V}{BHP} \leq Nr \tag{9}$$

Based on preliminary recommendations in the literature, it is reasonable to estimate emission cost values at $Tx =$ \$28.44/ton CO_2 increasing each year based on expected damage growth.

Exceeding this standard will result in costs ranging from \$28.44 to almost \$50 per ton of CO_2 emitted in 2050 and the cost to be added to the objective function (if the constraint 9 is not satisfied) is given by Equation (10).

$$\begin{cases} Tx \sum_{t=1}^{T} \left(\frac{E \times V}{BHP} - Nr \right) z_1 + Qta \sum_{t=1}^{T} \left(\frac{E \times V}{BHB} - Nr \right) z_2, \text{ si } \frac{E \times V}{BHP} > Nr \\ 0 \text{ otherwise} \end{cases} \tag{10}$$

with $z_i = \begin{cases} 1 \text{ if the strategy } i \text{ is chosen} \\ 0 \text{ otherwise} \end{cases} \quad \forall i \in \{1, 2\}$

$$z_1 + z_2 = 1$$

And $i \in \{1: \text{Carbon taxes}, 2: \text{Redemption of allowances}\}$

Step 7.

At first glance, the strategy of buying allowances seems more attractive given the difference between their price and that of carbon taxes. However, this price increased by 5% per year, it would possibly be judicious and less appropriate (even more commendable) for certain companies, to consider adopting the first plan to reduce their costs in the long term. To prove it, we carry out a numeral application which may help the decision makers to choose among these two strategies, the one which will guarantee an optimal cost. Through 6 scenarios, we will gradually reduce the cap limits from 627 g/bhp-h to 500 g/bhp-h (Table 7). Then, in 6 other scenarios (Table 8), we will increase the price by 5% annually and purchase one unit (in tons) of allowances. The results obtained through the increase in the purchase price of allowances are listed in Table 7, while those of the variation of the Nr standard appear in Table 8. The 5% annual increase in the allowance purchase price gave the results shown in Table 7. Gradually decreasing the cap limits from 627 g/bhp-h to 500 g/bhp-h gave the results shown in Table 8.

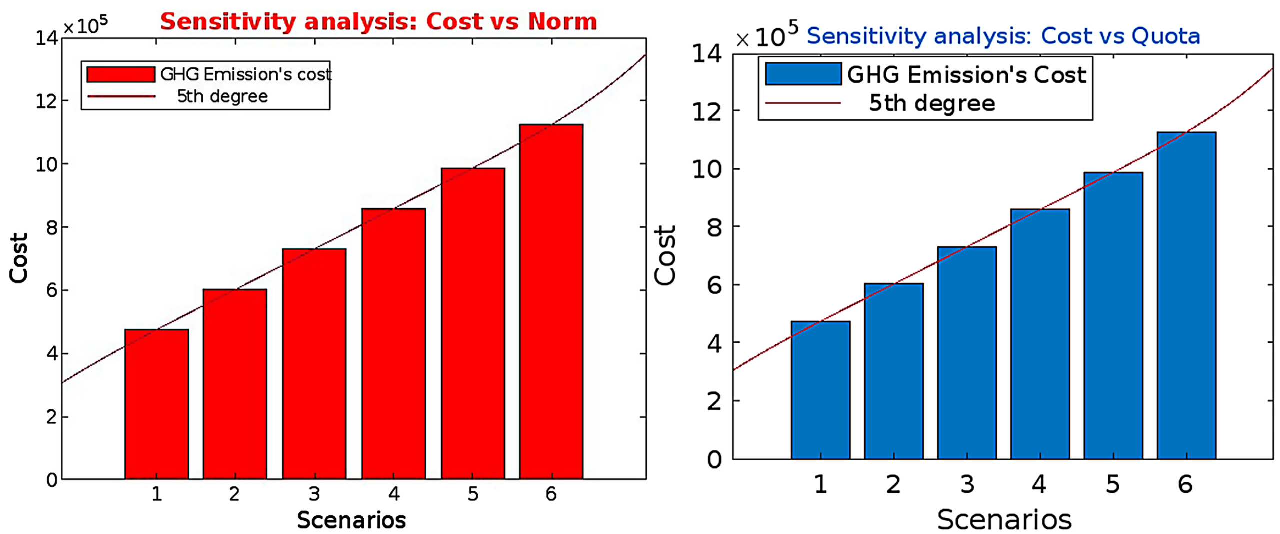
Through Figure 6, we observe the evolution of the cost of greenhouse gas

Table 7. Results of the variation of GHG emission standard.

Scenario	Varied parameter	Unit	Value	Emissions	Emission costs
1	Qta	$/t co2e	28.44	77.73t co2e	474663.6$
2			32		54080.0$
3			36		600840.0$
4			40		667600.0$
5			44		734360.0$
6			50		834500.0$

Table 8. Results of the variation in the purchase price of allowances.

Scenario	Varied parameter	Unit	Value	Emissions	Emission costs
1	Nr	g/bhp-h	627	77.73t co2e	474663.6$
2			602		602643.6$
3			577		730623.6$
4			552		858603.6$
5			527		986583.6$
6			500		1,124,802$



(a) (b)

Figure 6. Sensitivity analysis.

emissions according to the variation of the threshold described by the imposed standard (strategy 1). It clearly appears in this graph that as the scenarios represent a gradual drop of almost 4% of the tolerated threshold per g/bhp-h, the green cost generated increases rapidly until it reaches a value between 1 million and $1.2 million. This amount corresponds to the cost of $1,124,802 observed in scenario 6 of **Table 8**. **Figure 6** shows the evolution of the cost of greenhouse gas emissions according to the variation in the price of allowances (strategy 2). It also appears clearly in this graph that as the scenarios represent a gradual increase of nearly $4 per ton of CO_2 emitted, the green cost generated increases gradually until it reaches a value between 800,000 and 1 million bucks. This amount corresponds to the cost of $834,500 observed in scenario 6 of **Table 7**.

In view of these results, we see that it would be less costly in the long term for companies whose activities emit large quantities of *GHGs* to opt for the second strategy and consider buying allowances rather than having to pay the carbon tax, the generated costs of which shown in **Figure 6** increase more rapidly compared to the price of buying allowances.

4. Conclusions

The purpose of this work was to develop a compact urban waste management plan based on the principle of circular manufacturing and which can be adopted by different industries to meet their constraints optimize their profit while preserving planetary resources. To do this, we have gone through the recent literature studying the subject and have deduced a problem and issued objectives through its synthesis. The work done during this research identified the problem through a review of the synthesized literature and highlighted some recommendations. Indeed, the results obtained emphasized the need to carry out pre-sorting at the consumer's home. In practice, such a voluntary contribution should, in one way or another, be rewarded. Some manufacturers, such as *COCORICO* in France, have drawn up a contract binding them to the customer. It is stipulated that on the purchase of an item, a reduction in the price is made if the customer agrees to return the product when it becomes obsolete. This allows the manufacturer to recycle it to make new finished products.

Finally, the case study also demonstrated the importance of barcodes on packaging to identify the type of material to be recovered. Indeed, the proposed model had taken into consideration the different categories of plastics (*PET*, *HDPE*, *PVC*, *LDPE*, *PP* and *PS*) to make mono-material products. On the other hand, this cannot be envisaged for other types of materials, such as metals, for example, which nowadays do not have codes allowing their identification for recycling purposes. In this perspective, the proposed and implemented model can be further improved depending on the context. For example, a game theory could intervene in the optimization of its performance since consumers are Rational Entities that can act with the aim of achieving a gain.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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