Environmental Engineering and Management Journal May 2019, Vol. 18, No. 5, 1077-1088
http://www.eemj.icpm.tuiasi.ro/; http://www.eemj.eu

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A MULTI-OBJECTIVE OPTIMIZATION MODEL TO SUPPORT THE MUNICIPAL SOLID WASTE MANAGEMENT

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Abstract

This study aims to define a municipal Solid Waste Management (SWM) strategy using Multi-objective Optimization Problem (MOP) and ELECTRE method. Four waste treatment technologies were considered: recycling, composting, incineration and landfilling. Firstly, a Multi-objective Linear Programing (MOLP) model was developed. The solutions obtained from this model were ranked using the ELECTRE method. It was considered as case study a hypothetical city of 1,000,000 of inhabitants, presenting the average Brazilian waste per capita generation and composition. The results indicate 21 optimal solutions. The top ranked solution presents a combination of all the technologies considered. This solution presents the following waste allocation: 51.4% composted, 18.4% recycled, 16.7% landfilled and 13.5% incinerated. A sensitivity analysis was carried out by varying waste composition and criterion weights. The waste composition sensitivity was evaluated by substituting the average waste characteristics of Brazil to Europe, Japan and USA ones. The sensitivity analysis indicates that the ranking of solutions was very sensitive to waste composition changes and low sensitive to the variation of criterion preferences. Thus, although the MOP model presented is a simple approach for SWM when compared with other literature models, it shows to be efficient. The proposed model is able to decide between the trades-off related with the material allocation.

Key words: ELECTRE, Multi-objective Optimization Problem, Solid Waste Management, Weighted Sum Method

Received: April, 2016; Revised final: February, 2017; Accepted: June, 2017; Published in final edited form: May 2019

1. Introduction

About 1.3 billion tons of solid waste are annually generated in the world, and it is estimated that this amount will increase to 2.2 billion tons by 2025 (Hoornweg et al., 2012). Since Solid Waste Management (SWM) involves the ways which residues will be collected, transported, treated and disposed, it has been considered a challenging sector for municipal authorities in the 21th century (Aliakbari-Beidokhti et al., 2017; UNEP, 2009). According to Tchobanoglous et al. (1993), SWM consists in a complex process comprising a wide range of technologies and methods involving environmental and economic issues. Particularly, waste treatment is considered a crucial step in SWM, providing economic benefits and avoiding environmental liabilities by recovering materials and generating energy from waste (DEFRA, 2011; Schiopu and Gavrilescu, 2010). The waste treatment includes the choice of technologies and their integration, defining what technology could better handle each type of residue. Several technologies could be used individually or combined. The operational costs, material recovery, energy production and CO_2 emissions, job creation and wastewater generation of each technology have different values and requirements. In addition, treating some materials in order to improve one of these aspects might worsen another one. These

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characteristics lead to conflicting objectives which must be analyzed together (Zabeo et al., 2017).

This study aims to find an optimum SWM configuration using Multi-objective Optimization approach considering conflicting aspects. This decision consists in defining the technology which will treat each type and amount of material, maximizing the energy generation and materials recovery, and minimizing greenhouse gases emissions and operational cost. Then, in the next section a theoretical study about the Multi-objective Optimization, decision-making methods and similar studies are provided. After, the study methodology is detailed. Finally, the results are presented and discussed.

In this section the relevant subjects to the work will be discussed. First, a brief explanation about Multi-objective Optimization will be provided. Following, the aspects related to the decision-making will be broached and, finally, others similar studies will be presented.

1.1. Multi-objective optimization problems

In this part, it will be presented the main topics on the Multi-objective Optimization Problems (MOP), including mathematical formulation and resolution methods. After, the Weighted Sum Method is detailed. Using the MOP approach all the criteria of the objective functions are analyzed together, in order to reach compromised solutions which respect the technical constraints. The resolution of a MOP provides the mathematically best solutions considering all the possible ones. For this reason, in this work it will be used the MOP approach over others methods as Life Cycle Assessment (LCA) which is largely used for SWM studies.

1.1.1. Formulation and concepts

The MOP has the general formulation described by Eqs. (1-4):

$$min\ f(x) \in R^m, \quad x \in \Phi \tag{1}$$

Subject to:

$$\Phi = \begin{cases} g_j(x) \le 0, & i = 1,\dots,p \quad (1) \\ h_j(x) = 0, & j = 1,\dots,q \quad (2) \\ x \in X & \quad (3) \end{cases}$$

All the objective functions should be minimized simultaneously, but some of them are conflicting. This kind of problem has many solutions, providing a solutions set. In order to evaluate these solutions, for MOP there is the concept of dominance. One solution x_1 dominates another, x_2, if at least in one objective function the former is better than the latter, and the other functions values of x_1 are not worse than the ones of x_2. The dominance relation is described by Eq. (5):

$$f(x_1) \Rightarrow f(x_2) \tag{5}$$

Considering the solutions set, the solution $x*$ is considered a global optimum solution if (Eq. 6):

$$\neg x \neq \exists x^* \wedge x \in \Phi \ |f(x) \Rightarrow f(x^*), \quad f: X \subset \mathbb{R}^n \to Y \subset \mathbb{R}^m \tag{6}$$

All the global optimum solutions, called non-dominated or efficient solutions, correspond to the global Pareto-optimal set. Moreover, the image of the last one in the objective space is the Pareto front.

The cardinality of the Pareto front can be very high or even infinity. In practice, it is more interesting to estimate a finite and representative set of the efficient solutions. With the purpose of obtaining one point of the Pareto front, methods which transform the MOP into a Single Objective Problem (SOP) are used. However, before this approach it is necessary to normalize the objective functions, because they may have different units or orders of magnitude. One alternative is using Eq. (7):

$$\hat{f}_k(x) = \frac{f_k(x)}{f_k^{max}}, f_k^{max} > 0 \tag{7}$$

where f_k^{max} is the maximum value of the objective functionf_k. After, to transform MOP into a SOP it can be used:

- the Distance to a Reference Goal Method: it uses different norms, reference points and weights to transform the objective functions in one function;
- the Epsilon-constrained Method: it maintains just one objective function and transforms the others into constraints;
- the Weighted Product Method: it uses weights as exponents of the objective functions, transforming them in one function by the their product;
- the Weighted Sum Method: it transforms the objective functions into one by their weighted sum.

For this study, the Weighted Sum Method (WSM) will be used, so this is the one which will be described in the next section.

1.1.2. Weighted Sum Method

The WSM consists in transform the original MOP into the SOP by using a weighted sum of the objective functions. For the general formulation, the result problem is presented by the Eqs. (8-12):

$$\min_x\ w^t f(x) = \sum_{k=1}^{m} w_k f_k(x), x \in \Phi \tag{8}$$

Subject to:

$$\Phi = \begin{cases} g_j(x) \le 0, & i = 1,\dots,p \quad (4) \\ h_j(x) = 0, & j = 1,\dots,q \quad (5) \\ x \in X & \quad (6) \end{cases}$$

with:

$$\sum_{k=1}^{m} w_k = 1, w_k \geq 0 \quad (12)$$

The advantages of this method are the simplicity of the use and the required parameters are equal to the number of the objective functions. However, it is able to generate all Pareto optimal solutions only if the original MOP is convex (Ryu et al., 2009).

When this method is used to provide only a single Pareto optimal point, the decision maker's preferences are presumably embedded in the w_k parameters. On the other hand, the WSM may be used in an interactive way in order to obtain an approximation of the Pareto-optimal set. This approach requires the changing of the weights values and solving sequential optimization problems (Marler and Jasbir, 2004). Usually, it can lead to different optimal solutions, but, in some cases, with different weight values, the corresponding problems can converge to the same solution.

1.2. Decision-making

This topic will present the main concepts of the Decision-making, giving a brief explanation of the most largely used methods and detailing the ELECTRE method.

1.2.1. Decision-making methods

After obtaining an approximation of the Pareto-optimal set, the decision maker is facing with another question: choosing which solution to implement. To help in this task, there are many decision making methods. These methods intend to solve decision problems involving multiple and conflicting goals, coming up with a final solution that represents a good compromise considering the decision maker preferences information (Pole, 2008).

The decision making methods can be classified into two groups: the American and the French school. Among the methods for the former, it may be cited:

- Analytic Hierarchy Process (AHP): it is a theory of measurement through pairwise comparisons and relies on the judgments of experts to derive priority scales (Saaty, 2008);
- Multi-Attribute Utility Theory (MAUT): a structured methodology designed to handle the tradeoffs among multiple objectives using utility functions (Liu, 2012);
- Simple Multi-Attribute Rating Technique (SMART): this technique is based on a linear additive model, using a utility function for each criterion.

For the French school, the methods are based in outranking. The most famous are:

- Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE): The method uses an approach of flux in the graph of preferences;
- Elimination Et Choix Traduisant la Realité (ELECTRE): Obtain the outranking relations and the best actions using a concordance and a non-discordance threshold.

For the SWM is very important maintain more than one solution for the decision maker. So, in this study the ELECTRE method will be used and detailed in this section. The ELECTRE was chosen because of its robustness as a multi-criteria decision making tool and independence of subjective analysis.

1.2.2. ELECTRE method

The ELECTRE approach actually comprises a family of methods each one with some specificities. In this study it was adopted the ELECTRE II method. The first step of this method is defining the weights for each criterion *j*, with $j \in J=\{1,..,c\}$. After, the comparisons between the alternatives a_i and a_k considering the criteria, g_i, are made building the sets of the Eqs. (13-15):

$$J^{+}(a_i, a_k) = \{j \in J | g_j(a_i) > g_j(a_k)\} \quad (13)$$

$$J^{=}(a_i, a_k) = \{j \in J | g_j(a_i) = g_j(a_k)\} \quad (14)$$

$$J^{-}(a_i, a_k) = \{j \in J | g_j(a_i) < g_j(a_k)\} \quad (15)$$

Then, the relations between the alternatives are converted into numerical values, using the weights p_j described by Eqs. (16-18):

$$P^{+}(a_i, a_k) = \sum_j p_j,\ j \in J^{+}(a_i, a_k) \quad (16)$$

$$P^{=}(a_i, a_k) = \sum_j p_j,\ j \in J^{=}(a_i, a_k) \quad (17)$$

$$P^{-}(a_i, a_k) = \sum_j p_j,\ j \in J^{-}(a_i, a_k) \quad (18)$$

With these values, the concordance index is calculated as the Eq. (19):

$$C_{ik} = \frac{P^{+}(a_i, a_k) + P^{=}(a_i, a_k)}{\sum_{j \in J} p_j,} \quad (19)$$

and the non-discordance index by the Eq. (20):

$$D_{ik} = \begin{cases} 0 \text{ if } J^{-}(a_i, a_k) = \phi \\ \delta \max(g_j(a_k) - g_j(a_i)), j \in J^{-}(a_i, a_k) \text{ otherwise} \end{cases} \quad (20)$$

The outranking relation between the alternatives, a_i is preferred or indifferent in relation to a_k ($a_i S a_k$), is made by Eq. (21):

$$a_i S\, a_k = \begin{cases} C_{ik} \geq \tau_C \\ D_{ik} \leq \tau_D \end{cases} \quad (21)$$

where τ_C is the concordance index (usually 0.7) and τ_D is the non-discordance index (usually 0.3). Although the relation is defined between two alternatives, for the most part of the applications there are more solutions. So, for the solutions that $a_i S a_k$, it can be built a graph $G=(V,A)$, in which V is the set of vertices (alternatives) and A is the set of arcs (outranking relations). For a large number of alternatives, building this graph is not trivial. Then, the distillation method described in Rogers and Aidan (2012) and Hokkanen and Salminen (1997) can be used.

For the distillation process the alternatives are classified by the number of solutions which they outrank. So, the first position contains the solutions that most outranks others. After, the alternatives are classified by the number of solutions which outrank them. Then, the first position contains the solutions that are less outranked. The final ranking is determined by the average between the two classifications. However, in case the two rankings are not close, *i.e.*, the alternative is the first in one ranking and the last in the other, the solution can be considered incomparable (Hokkanen and Salminen, 1997).

1.3. Optimization applied to SWM

Decision making methods have been widely applied in waste management sector, *e.g.* Hokkanen and Salminen (1997), Vego et al. (2008), Madadian et al. (2013), Coban et al. (2018) and Abdullah et al. (2019). But, the alternatives of these studies are not a solution from Pareto-optimal set. They use these methods to evaluate practical solutions. According to Soltani et al. (2015) the majority of studies involving decision making methods to assess SWM have used AHP approach, followed by ELECTRE and PROMETHEE methods. The same author also shows that the most part of papers in this sector focus on two concerns: landfill location selection and waste treatment technology choice.

Many works applied the optimizations tools in the SWM. Here, the focus is on the MOP approaches used in this area. The work Chang and Wang (1996) applied Multi-objective Mixed Integer Programming (MOMIP) techniques in SWM. Their model has four objectives that include the aspects of: economics, noise control, air pollution control and traffic congestion limitation. In order to obtain the efficient solutions they used the Distance Based Compromise Programming method. The case study in the city of Kaohsiung in Taiwan is included as a demonstration.

The study Minciardi et al. (2008) built a Nonlinear Multi-objective Optimization Problem (NLMOP). Furthermore, four aspects were considered as objectives: economic costs, unrecycled waste, sanitary landfill disposal and environmental impact. An interactive reference point procedure has been developed and they made a case study in Geneve, Italy.

Ahani et al. (2019) presented a Multi-objective optimization model for municipal waste management using two objectives: environmental costs minimization and economic costs minimization. The aforementioned paper, selected Tehran in Iran, as the case study.

2. Materials and methods

In order to achieve the objectives of this study, a global process presented by Fig. 1 was built.

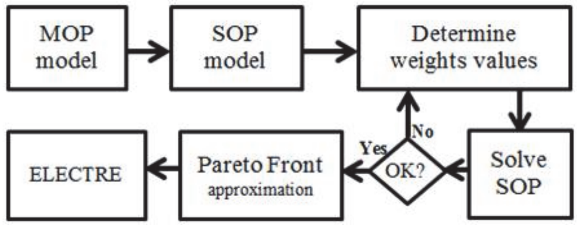

Fig. 1. The global process of the study

The first step of the study concerns to model the SWM situation as a MOP. For feeding the model, the data of the SWM for medium size city was taken. Then, the MOP was transformed into a SOP by the weighted sum of the normalized objectives, *i.e.* WSM. By varying the weights values, the Pareto Front approximation of the problem was taken. Finally, the ELECTRE method was applied in the decision making step. This process was implemented in Matlab. In the next subsections, these steps will be detailed.

2.1. The mathematical model

For the MOP model, the sets are:

- I: the set of solid waste types, with $i \in \{1, 2, 3, 4, 5, 6\}$, where 1 represents the paper category, 2 the glass, 3 the metal, 4 the plastic, 5 the organic material and 6 others;
- J: the set of technologies to process the solid waste, with $j \in \{1, 2, 3, 4\}$, where 1 represents the recycling plant, 2 the composting plant, 3 the incinerator and 4 the landfill.

The variables of the problem are:

- x_{ij}: the amount of material i directly processed by the technology j **;**

The problem parameters are:

- C_{ij}: the cost of processing material i by the technology j;
- p_{ij}: the material i remaining rate after processing by the method j that must be disposed to the landfill;
- t_{ij}: the energy production rate by the technology j for the material i;
- r_{ij}: the greenhouse gases generation rate by the technology j;
- W_i: the total of solid waste of the type i;
- e_j: the job created by the usage of thecnology j;
- l_j: wastewater generation by the usage of thecnology j.

The model has six objective functions related to: energy generation, greenhouse gases emissions, materials recovery, operational cost, job generation and wastewater generation. The first objective function, f_1, aims to maximize the electrical energy generation (Eq. 22).The first part of the function corresponds to the energy provided by the solid waste transported to the different technologies. The second one corresponds to the energy provided by the remaining material from the recycling plant:

$$\max_x f_1 = \sum_{j=1}^{4}\sum_{i=1}^{6} t_{ij}x_{ij} + \sum_{j=1}^{2}\sum_{i=1}^{6} t_{i4}p_{ij}x_{ij} \quad (22)$$

The second objective, f_2, aims to minimize the greenhouse gases emissions produced by the processing of the materials in each technology (Eq. 23):

$$\min_x f_2 = \sum_{j=1}^{4}\sum_{i=1}^{6} r_{ij}x_{ij} + \sum_{j=1}^{2}\sum_{i=1}^{6} r_{i4}p_{ij}x_{ij} \quad (23)$$

The third objective, f_3, aims to maximize material recovery, which includes the paper, glass, metal and plastic for the recycling plant and the organic material for the composting plant (Eq. 24):

$$\max_x f_3 = \sum_{i=1}^{4} x_{i1} + x_{53} \quad (24)$$

The fourth objective, f_4, aims to minimize the cost of the system (Eq. 25):

$$\min_x f_4 = \sum_{j=1}^{4}\sum_{i=1}^{6} C_j x_{ij} + \sum_{j=1}^{3}\sum_{i=1}^{6} C_4 p_{ij}x_{ij} \quad (25)$$

The fifth objective, f_5, aims to maximize the job generation of the system (Eq. 26):

$$\max_x f_5 = \sum_{j=1}^{4}\sum_{i=1}^{6} e_j x_{ij} \quad (26)$$

The sixth objective, f_6, aims to minimize the wastewater generation of the system (Eq. 27):

$$\min_x f_6 = \sum_{j=1}^{4}\sum_{i=1}^{6} l_j x_{ij} \quad (27)$$

The constraints of the problem aim to guarantee the respect to the mass balance, capacity and material processing possibilities. The first type is the mass balance for all the types of material (Eq. 28):

$$\sum_{j=1}^{6} x_{ij} = W_i \text{ with } i = 1,2,3,4,5,6 \quad (28)$$

The composting plant uses only organic material as described by Eq. (29):

$$\sum_{i=1}^{4} x_{i2} + x_{62} = 0 \quad (29)$$

The Eq. (30) determines that the recycling plant does not use organic material:

$$x_{51} = 0 \quad (30)$$

The others type of material goes only to the incinerator or the landfill (Eq. 31):

$$\sum_{j=1}^{2} x_{6j} = 0 \quad (31)$$

The domain of the variables is defined by Eq. (32):

$$x_{ij} \geq 0 \ \forall i \in I \ e \ \forall j \in J \quad (32)$$

The MOP model is linear and constrained. So, considering that it is a convex problem, the WSM can be applied to obtain the Pareto front approximation.

2.2. Input data

For the case study presented in this paper it was considered a hypothetical city with 1,000,000 of inhabitants. Concerning the waste generation, according to the Brazilian National Sanitation Information System (BNSIS, 2016), Brazilian cities with a population in the range of 500,000 to 1,000,000 inhabitants present a daily waste per capita generation of 1.00 kg. So, based on this data, the average daily amount of MSW to be managed for the city under study is equal to 1,000 tons.

The following waste fractions were considered in this study: paper, glass, metal, plastic, organic and others. The latter groups some existing materials, which individually are not quantitatively representatives, as cigarettes, leaves, wood and inert materials. It was assumed that 50% of the fraction others comprises organics and 50% consists in inert materials. It was assumed a municipal solid waste composition based on Brazilian data provided in Foundation to Support the Development of the Federal University of Pernambuco - FADEUFPE (2014) and presented in Table 1.

Table 1. MSW waste composition adopted in this study (FADEUFPE, 2014)

Waste Composition	***Brazil [%]***
Paper	13.1
Glass	2.4
Metal	2.9
Plastic	13.5
Organic	51.4
Others	16.7

The Fig. 2 shows the waste treatment streams for municipal waste management considered in this study. The waste treatment technologies evaluated were: composting, recycling, incineration with energy recovery and landfilling with energy recovery.

Table 2 presents the operational costs related to each waste treatment technology based on Brazilian context. Job creation and wastewater generation for each technology are also presented in Table 2. Wastewater generation includes all effluents produced in each technology including leachate from landfills.

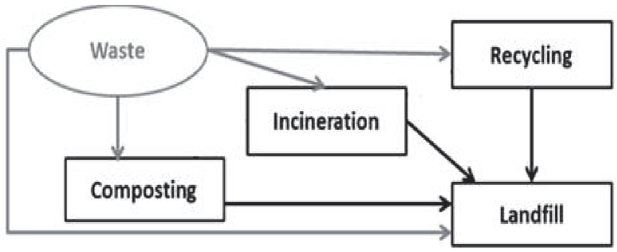

Fig. 2. Solid Waste Management scheme

Regarding CO_2 emissions, Table 3 presents the values adopted in this study for each waste treatment technology. Negative values for CO_2 emissions from recycling plants mean that recyclables recovered avoid releases for materials production from virgin resources. Table 3 also presents the electricity generation in each technology as provided in State Environmental Foundation – FEAM (2010) and FADEUFPE (2014). In addition some assumptions were made for each technology. Concerning composting and recycling, the former treats only organic waste while the latter recovers only paper, glass, metal and plastic. Incineration receives all waste types allowing waste volume reduction and electricity generation, but this alternative doesn't allow material recovery. Alternatively, waste could be directly disposed in the landfill. It is important to note that, as stated by Thorneloe and Weitz (2004), independently of the used treatment there is always a certain amount of waste to be managed.

Table 3 also presents the remaining percentage of total waste processed in a treatment facility that needs to be landfilled. The remaining rejects from incineration corresponds to inert materials and could not be used for energy recovery in landfills.

2.3. Resolution

In order to obtain the Pareto front approximation, the SOP was interactively solved by the *linprog* function on Matlab. A set of 98 weights values combinations was determined to increase the diversity of solutions. Although the 98 problems have had different weight values, many of them converged to the same solution.

Table 2. Waste facility operational costs, wastewater generation and job creation (FADEUFPE, 2013, 2014)

Technology	***Operational costs [U$/ton]***	***Job creation [job/ton]***	***Wastewater generation [m³/ton]***
Composting	2.00	2.00	0.15
Incineration	27.50	0.05	0.20
Recycling	25.00	5.00	0.05
Landfilling	9.00	0.30	0.20

Table 3. Energy generation and CO_2 emissions for each waste facility

Technology	***Waste fraction***	***CO_2 emissions [CO_2TEQ/ton] (Abreu, 2011; Manfredi et al., 2009; Mcdougall et al., 2001)***	***Electricity generation [kWh/ton] (FADEUFPE, 2014; FEAM, 2010)***	***Waste remaining quantities [%] (Den Boer et al., 2005; FEAM, 2010)***
Composting	Paper	0	-	100
	Glass	0	-	100
	Metal	0	-	100
	Plastic	0	-	100
	Organic	0.16	-	5
	Others	0	-	100
Recycling	Paper	199e-3	-	30
	Glass	-88e-3	-	30
	Metal	-4.5	-	30
	Plastic	-1.3	-	30
	Organic	0	-	100
	Others	0	-	100
Incineration	Paper	1,279	440	5
	Glass	0.059	0	100
	Metal	0	0	50
	Plastic	2.7	1200	3
	Organic	0.58	500	3
	Others	0.29	250	50
Landfilling	Paper	1.09	0	-
	Glass	0	0	-
	Metal	0	0	-
	Plastic	0	0	-
	Organic	0.41	200	-
	Others	0.2	100	-

Then, it was necessary to make a procedure that selected the different solutions. Thus, the set of distinct solutions went to the decision-making process.

2.4. Decision-making process

In SWM studies is common the use of decision-making methods to evaluate practical solutions. But, here, the use is with the Pareto-optimal set. For this problem, there is preference to use outranking methods. In this case, the non-dominated solutions are evaluated and ranked, not rejected. This perspective is useful for the practical aspects, where the decision makers can compare their real solutions to the compromising solutions achieved. At the first, the ELECTRE II method satisfies the condition. The objective functions values will be used as the criteria.

2.5. Sensitivity analysis

The sensitivity analysis was carried out to assess the effect of changes in input data and in decision making preferences in the final result. The former was evaluated by varying the composition of waste whereas the latter was assessed using different set of preference weights on the ELECTRE II method to rank the non-dominated solutions. For waste composition sensitivity analysis the initial input data was changed by using three other MSW compositions. Three scenarios was created. These scenarios present the same hypothetical city of 1,000,000 inhabitants with the same daily waste per capita generation of the 1 kg, but the waste composition was changed. Instead of Brazilian waste composition, each scenario presents different waste characteristics, corresponding to the ones of Japan, Europe and USA. Each scenario corresponding to the typical MSW composition from European Union, United States (USA) and Japan. Table 4 presents the waste composition of Japan, Europe and USA adopted in the sensitivity analysis.

Table 4. Waste composition for sensitivity analysis scenarios (FADEUFPE, 2014; Fraunhofer Institute for Building Physics – FIBP, 2014; Zhang et al., 2010)

Waste Composition	*Europe [%]*	*Japan [%]*	*USA [%]*
Paper	29	33	28.5
Glass	11	5	4.6
Metal	5	3	9
Plastic	8	13	12.4
Organic	31	34	27.1
Others	16	12	18.4

Regarding decision making preference, the sensitivity analysis was carried out considering four weight scenarios, each one assigning the double of importance to one of the criteria. For the sensitivity analysis of weights, it was assumed the Brazilian waste composition, as presented in the base scenario. Table 5 presents the criteria weights adopted in each scenario for sensitivity analysis of weights.

3. Results and discussions

In the Brazil case, for the Pareto Front approximation was taken 21 distinct solutions from 98 weight combinations values. Fig. 3 presents the waste allocation for each solution. It is noted a high diversity of optimal solutions, with very different allocation results. It is observed that composting and incineration are competing technologies. Then, the higher the participation of the incineration, the lower the participation of the composting, or vice versa. This was expected because on the one hand organic waste fraction presents a high potential for energy recovery from incineration plants and on the other hand material recovery from organic fraction is the function of composting plants.

In addition, the results evidence the important role of recycling to reduce the amount of waste landfilled. Indeed, only in alternatives 3, 4, 5, 11 and 14, which present the highest use of recycling, the landfill destination corresponds to less than 20% of the total waste mass. Another important observation is the fact that landfilling represents less than 50% of waste destination for 17 optimal solutions, whereas currently in Brazil landfills and dumps were used as final destination for almost the totality of the waste (Brazilian Association of Urban Cleaning Companies and Special Waste - ABRELPE, 2018). Thus, these results suggest that the current waste management practices in this country need to be changed, mainly substituting landfilling by other waste treatment technologies more environmentally friendly.

Table 6 presents the detailed solution results showing residues allocation for each waste fraction. Analyzing all the solutions it is noted that paper and glass were preferentially allocated to recycling and landfilling over incineration. This is probably related to the fact that the former presents a lower job generation rate and a higher operational costs and CO_2 emission rate than the formers. Metal waste fraction was principally allocated to recycling, mainly due to the CO_2 emissions avoided.

For plastic waste fraction in turn, the preferential technology was incineration, which was expected because this fraction presents a high potential for energy recovery by thermal treatments. Referring to organics, as it allows energy generation in incinerators and material recovery in composting plants, the solutions obtained present different organic allocation results. So, globally it is noted a preference for composting and incineration as destination for this type of waste. Others waste fraction was also mostly sent to the landfill.

Concerning objective function results, Table 7 presents the values obtained for each solution. For the objective f_1 related to energy generation maximization, solutions 19, 20 and 21, which have focus on incineration, presented the highest energy generation results. Referring to the objectives f_2 and f_3, solution 5 that emphasizes on composting and recycling, obtained the best score for both objectives.

Table 5. Objective function weights for each sensitivity analysis scenario

Objective functions label	***Criteria weights***						
	Base Scenario	***Scenario 1***	***Scenario 2***	***Scenario 3***	***Scenario 4***	***Scenario 5***	***Scenario 6***
f_1	1	2	1	1	1	1	1
f_2	1	1	2	1	1	1	1
f_3	1	1	1	2	1	1	1
f_4	1	1	1	1	2	1	1
f_5	1	1	1	1	1	2	1
f_6	1	1	1	1	1	1	2

Table 6. Waste fraction allocation for each optimal solution

Waste fraction	***Treatment technology***	***Waste allocation by solution [tons]***																				
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Paper	Recycling	0	0	131	131	131	0	0	0	131	0	131	0	0	131	0	131	0	131	0	0	0
	Composting	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Incineration	0	0	0	0	0	0	0	0	0	131	0	0	0	0	131	0	0	0	131	131	131
	Landfilling	131	131	0	0	0	131	131	131	0	0	0	131	131	0	0	0	131	0	0	0	0
Glass	Recycling	0	0	24	24	24	0	0	0	24	24	24	0	0	24	0	24	0	24	0	8	24
	Composting	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Incineration	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0
	Landfilling	24	24	0	0	0	24	24	24	0	0	0	24	24	0	24	0	24	0	24	7	0
Metal	Recycling	0	29	29	29	29	29	0	29	29	29	29	0	29	29	0	29	29	29	0	9	29
	Composting	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Incineration	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	0
	Landfilling	29	0	0	0	0	0	29	0	0	0	0	29	0	0	29	0	0	0	29	8	0
Plastic	Recycling	0	0	135	135	135	0	0	0	0	0	135	0	0	135	0	0	0	0	0	0	0
	Composting	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Incineration	0	0	0	0	0	0	135	135	135	135	0	135	135	0	135	135	135	135	135	135	135
	Landfilling	135	135	0	0	0	135	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Organic	Recycling	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Composting	514	514	514	514	514	0	514	514	514	514	0	0	0	0	0	0	0	0	0	0	0
	Incineration	0	0	0	0	0	0	0	0	0	0	514	0	0	514	0	514	514	514	514	514	514
	Landfilling	0	0	0	0	0	514	0	0	0	0	0	514	514	0	514	0	0	0	0	0	0
Others	Recycling	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Composting	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Incineration	0	0	0	76	167	167	0	0	0	0	0	0	0	77	0	0	167	167	167	167	167
	Landfilling	167	167	167	91	0	0	167	167	167	167	167	167	167	90	167	167	0	0	0	0	0

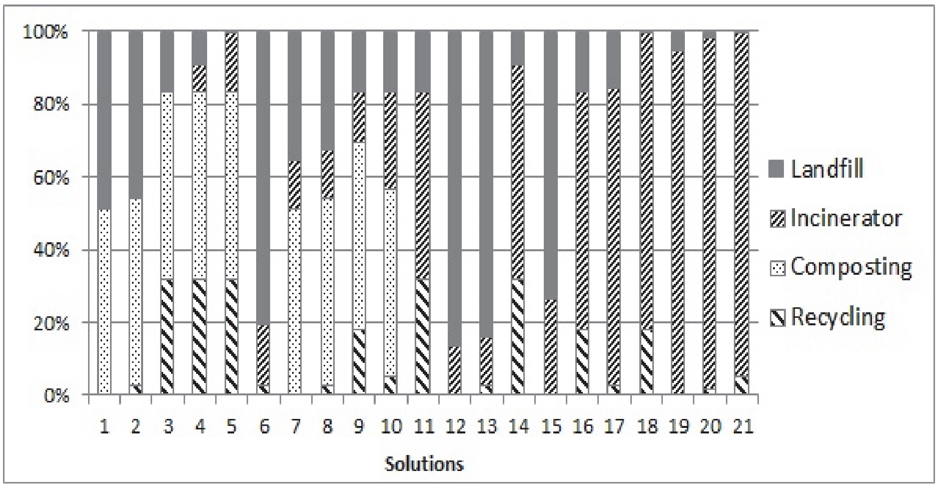

Fig. 3. Waste allocation for each optimal solution

Solutions 3 and 4 were also the best ones in terms of objective f_3. Regarding the objective f_4 linked to operational costs minimization, the best solution was the number 1 based on composting and landfilling. This was expected as these are the cheapest technologies evaluated in this study. Considering objective f_5, solution 3 presented the best result. It was expected as it has a focus on recycling and composting, the better technologies considered in terms of job generation. For objective f_6, solutions 3, 4 and 5 presented the lower wastewater generation results.

The Fig. 4 shows the normalized objective functions values, because the original values have different units and order of magnitude. In Fig. 4 it is possible to see the crossed lines between the objectives 1 and 2, and 2 and 3. This reveals the conflict between the aspects considered in each function. These conflicts are due to the material allocation: if the material is recovered, the objective f_2, then there is less material for the incineration process, which has the highest energy production and emission rates, the objectives f_1 and f_3, respectively. It is worth mentioning that solutions with high levels of energy production or material recovery often present high costs. This fact can be assigned to the elevated costs of the incineration and recycling. Considering the classification of solutions using equal weights for the different criteria (base scenario), Table 8 presents the solutions ranked according to ELECTRE method. From the results it is observed that the 21 solutions were classified in 10 levels.

Table 7. Objective functions results for each solution

Solution	***f_1 (kWh/ton)***	***f_2 (tonCO$_2$eq/ton)***	***f_3 (ton/ton)***	***f_4 (U$/ton)***	***f_5 (job/ton)***	***f_6 (m^3/ton)***
1	21840.0	407.8	514.0	5633.3	1173.8	174.3
2	21840.0	277.3	543.0	6175.6	1310.1	170.0
3	21840.0	25.8	833.0	11598.6	2673.1	126.5
4	33274.9	18.2	833.0	13351.9	2654.0	126.5
5	46890.0	9.1	833.0	15439.6	2631.4	126.5
6	144550.0	378.6	29.0	13383.3	394.6	195.7
7	183840.0	772.3	514.0	8167.3	1140.1	174.3
8	183840.0	641.8	543.0	8709.6	1276.4	170.0
9	183840.0	565.8	698.0	11608.1	2004.9	146.7
10	241480.0	168045.9	567.0	11640.8	1356.4	166.4
11	273700.0	231.2	319.0	24613.1	1670.8	152.2
12	281500.0	890.3	0.0	11534.0	266.3	200.0
13	281500.0	759.8	29.0	12076.3	402.6	195.7
14	285192.1	223.5	319.0	26375.2	1651.7	152.2
15	339140.0	168296.5	0.0	14016.4	233.5	200.0
16	435700.0	771.2	184.0	24622.5	1002.6	172.4
17	460750.0	830.5	29.0	25565.0	232.3	195.7
18	460750.0	754.5	184.0	28463.5	960.8	172.4
19	518390.0	168367.2	0.0	27505.2	63.3	200.0
20	518390.0	168325.6	17.0	28336.3	137.8	197.5
21	518390.0	168234.6	53.0	28496.3	312.4	192.1

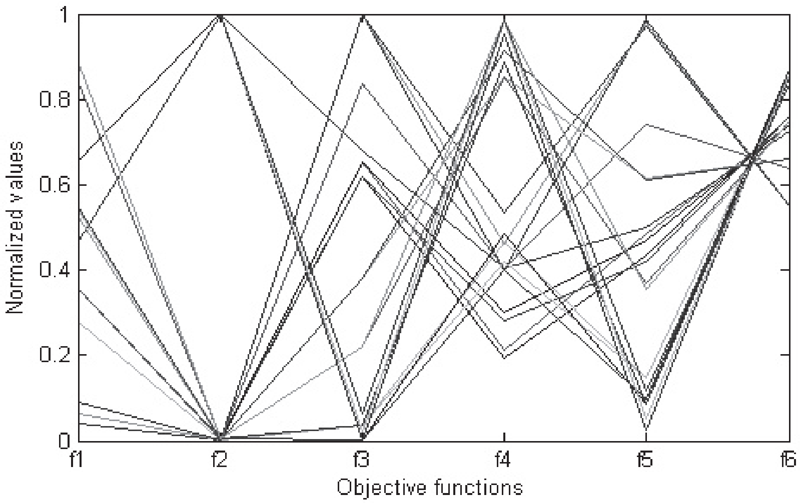

Fig. 4. The objective function values of the Pareto front approximation

Solution 9 was the first of the ranking. This solution proposes a waste management strategy that combines all technologies considered. As observed in Fig. 3, in solution 9 the composting waste corresponds to 51.4% of the total, followed by recycling, landfilling and incineration with 18.4%, 16.7% and 13.5%, respectively. From Table 6, this solution suggests to process all the organic material by composting. Plastic waste fraction was totally processed in incineration, which it is expected because this material presents a high calorific potential. Metals, paper, glass were allocated to recycling plants. The category others was sent to landfill. So, the first position in raking for solution 9 are justified by the allocation of waste types to different technologies allowing optimize the benefits from each waste fraction according its characteristics resulting in a good compromise among the objective functions.

Table 8. Solutions ranking according ELECTRE methodology

Solution label	*Ranking position*
9	1
16	2
3	3
8	3
18	4
2	5
4	5
13	5
5	6
7	6
10	6
11	6
14	6
17	6
21	6
1	7
12	7
20	7
15	8
19	9
6	10

Considering sensitivity analysis related to criteria weights, from Fig. 5 it is observed that globally the ranking was very similar among scenarios. Scenarios 3 and 6 present the same ranking. The latters present 50% of its classifications equal to ones of Base Scenario, Scenario 4 and 5. However, it is noted that scenario 1 and 2, in which energy generation and material recovery presents the double of the weight of the other objectives, respectively, only 30% of solutions present the same ranking of the Base Scenario. Indeed, in this scenario, the highest importance of energy recovery has caused an important change in ranking mainly because the solutions with the high energy production levels and material recovery rates present low performance results for other objective functions.

In addition, all scenarios are in agreement about the first ranked solution. Indeed, for all scenarios solution 9 reached the firs position in the ranking. Referring to sensitivity analysis involving waste composition variations, the waste management strategies suggested by the MOP were very sensitive to waste composition. Indeed, for the three waste characterization presented in Table 4, the results present more solutions focused on recycling waste than in the base scenario. This is probably related to the lower participation of organics in the total waste mass of these three scenarios when they are compared to the base scenario. Fig. 6 presents the waste allocation for the top ranked solutions for each waste composition scenario. It is important to note that according to ELECTRE II classification method two configurations are presented at the first position for Europe scenario. From Fig. 6 it is observed that no scenario presented a top ranked solution similar to the one of the base scenario.

For the Japanese waste composition scenario, the results recommend a waste management strategy focused on landfilling and composting. For Europe it was observed in the two top ranked solutions a predominance of incineration. Concerning the results for USA waste composition as well as for the third Europe top ranked solution, it is noted a predominance of landfilling followed by incineration. Thus, these results indicate that each SWM system needs to be analyzed according its specific characteristics and there is no best waste management strategy applicable to all cases.

4. Conclusions

From the results, it is noted the top ranked solution presents a combination of all the technologies considered. This indicates that waste management strategies based on multiple waste treatment technologies integration provide better performance than the concentration on only one type of treatment process. The sensitivity analysis indicates that the ranking of solutions was very sensitive to waste composition changes and low sensitive to variations of criterion preferences.

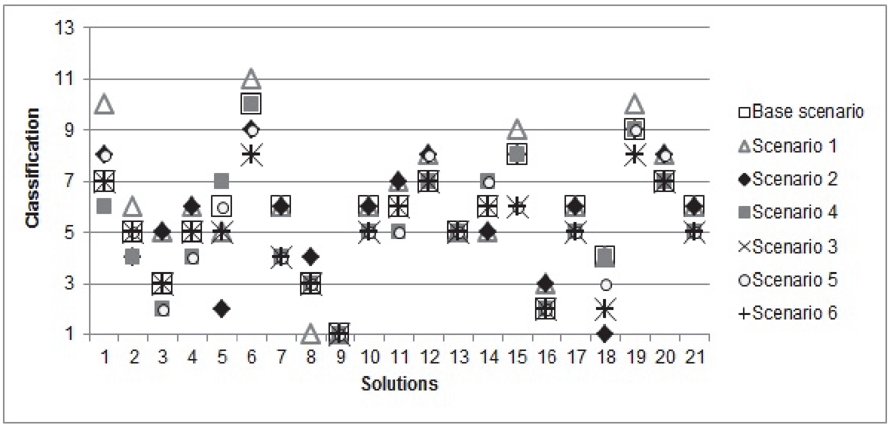

Fig. 5. Results of sensitivity analysis for criteria weight changes

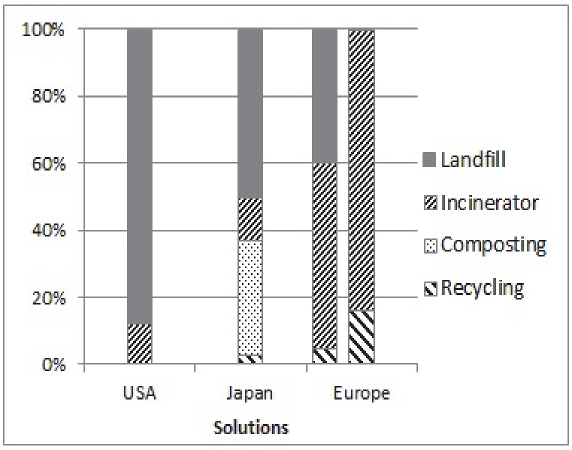

Fig. 6. Waste allocation for the top ranked solutions for each waste composition scenario considered in sensitivity analysis

Thus, although the MOP model presented is a simple approach for SWM when compared with literature models, it shows to be efficient. The proposed model is able to decide between the trades-offs related with the material allocation. The ELECTRE method served satisfactorily to the aim of the study, as it responded to some parameters changes and all solutions were preserved.

For future works, other methods to transform the MOP into a SOP can be used, and other decision making methods based on outranking, as PROMETHEE, may be implemented.

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