Global Scientific JOURNALS

GSJ: Volume 8, Issue 10, October 2020, Online: ISSN 2320-9186
www.globalscientificjournal.com

Multi Criteria Analysis for Integrated MSW Management in Sao Paulo City

E.R. Silva (1), G. Mondelli (1)

1: Center of Engineering, Modelling and Social Applied Sciences, Federal University of ABC – Avenida dos Estados, 5001, Santo André-SP, Brazil

Abstract: The environmental concern with the treatment and final disposal of municipal solid waste (MSW) generated in cities has increased worldwide. In São Paulo, the largest city of the Latin America, the use of sanitary landfills is preponderant and initiatives that incorporate treatment technologies that recovery recyclable materials, compost and generate energy are insipient. In this context, the main objective of this paper is to evaluate the treatment technologies for integrated MSW management and propose the better treatment scenario that incorporates the segregation of the MSW recoverable fractions and reduce the final disposal into the sanitary landfills. Secondary data of gravimetric analyzes conducted between 2017 and 2018 of the southeast region of São Paulo City were used to simulate a mechanic segregation model. The result of this sorting contributed to modeling five scenarios and these ones were compared to the current scenario, which is (1) 2% of selective collection and 98% to the landfill. The other scenarios are: (2) Scenario 1 added by two mechanical biological treatment units (MBT); (3) An increase of 150% in selective collection, added by two thermal treatment units; (4) 2% of selective collection, two MBTs and 2 thermal treatment plants; and (5) same of scenario 4, but without compost sale. In view of the survey of environmental, financial, social and technical factors of each scenario, the TOPSIS method was used, which orders the preference for similarity of the ideal solution. As a result, the scenario 4 is the better solution, reducing the current mass going to the landfill in 80 %. In Brazil, the use of waste treatment technologies in large cities is incipient, so it is extremely important the study of solutions that minimize the damage generated by society on the environment.

Key words: Multi Criteria Decision Making (MCDM), Analytical Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Material Recovery Facility (MRF), Mechanical Biological Treatment (MBT), Waste to Energy (WtE).

1. INTRODUCTION

In most countries, the local authorities in charge of the waste collection, encourage initiatives of post-consumer recycling and select the best suitable alternatives for treating their waste (Antonopoulos et.al., 2014). The landfill waste diversion is an ordinary goal among the countries, due the potential environmental liabilities, the area required to implement new landfills and the environmental resources preservation. Thus, facing the characteristics of the waste produced at each site and the treatment technologies available, the selection of the most efficient scenario requires from the authorities a detailing of their needs, wishes and strategies. In this context, decision-makers often need fast and effective tools to model and optimize alternatives that meet defined conditions and compare them according to specific criteria.

Multicriteria Decision Making (MCDM) analysis is a tool that incorporates the values of individual judgments from decision-makers or multiple stakeholders in order to achieve the best decision. The MCDM employ different optimization methods to rank the alternatives in order to select an optimal alternative or to differentiate between acceptable and unacceptable ones (Vucijac et.al., 2016).

Among the MCDM alternatives available in the literature, to choose the model that finds a more sustainable solution for waste management, the Analytical Hierarchy Process (AHP) method is used to obtain the weights, and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method to calculate the best scenario proposed.

The TOPSIS method was also used by Pires et al. (2011), Vucijak et al. (2016), Maghajani Mir et al. (2016) and Ali et al. (2018) as a tool to optimize integrated MSW management models.

Initially, the TOPSIS algorithm begins with the survey of the decision criteria for choosing the best scenario, whose information will form a matrix. Then, the values of the matrix are multiplied by the weights of each criteria.

Thereafter, positive and negative solutions are calculated in relation to the ideal. The distance of each alternative to the ideal solution is calculated with a distance measurement. Finally, the alternatives are classified based on their proximity to the ideal solution.

For the step of weighting the criteria, the analytical hierarchy process (AHP) was proposed by Saaty (1980) and represents one of the most important techniques for multi-criteria decision models, which makes it possible to establish weights for different criteria (Pires et.al., 2011; Saaty, 1994). Pairwise comparisons between criteria are used to obtain the weight related to the importance of each criterion, which improves data consistency. The AHP method is used at this phase where the TOPSIS method is deficient, which means that while the former establishes the definition of weights, the latter calculates the order of priority of the scenarios (Pires et. al, 2011).

Based on this, the present paper has the objective to assess different scenarios for integrated MSW management, considering the implementation of mechanical biological treatment units, products processing and thermal treatment units, aiming reduce the final disposal into the sanitary landfills reducing the amount of waste disposed of in the landfill, using the AHP and TOPSIS methods. The study case applied for the Southeast Region of the São Paulo City, considering real data and current infrastructure use, brings a light for the MSW management in the biggest cities of the developing countries, where there is a lack of sustainable solutions applied into the scientific practice.

2. MATERIALS AND METHODS

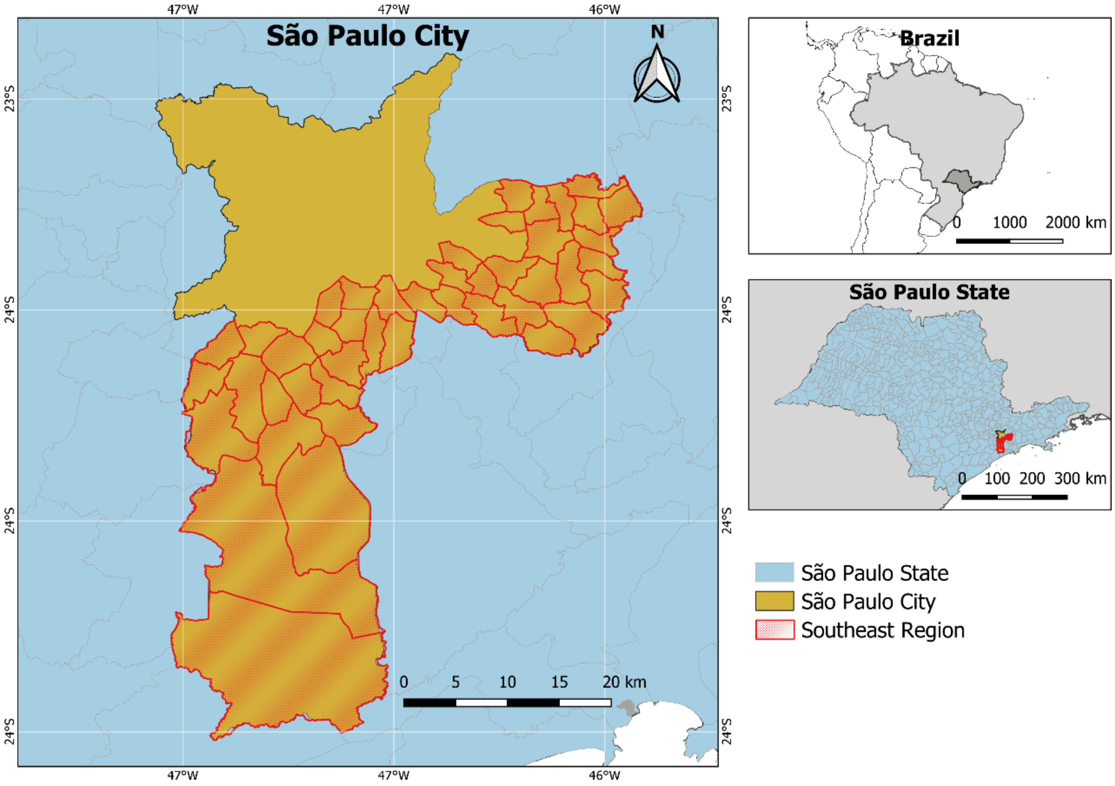
The study methodology started with the survey of the gravimetries' secondary data performed in the Southeast region of the São Paulo City in the years 2017 and 2018, which were used to prepare the mass balance for the mechanical treatment or Material Recovery Facity (MRF) model. Then, the integrated waste management scenarios were thought for comparison with each other, based on the mass balance from real gravimetric data. For the scenarios' assessment, quantitative and qualitative criteria were defined, and finally, for chosen the best model, were applied the AHP method, that defines the weights of each criteria, and TOPSIS method, that choose the closest scenario to the ideal one, according to the established criteria.

2.1. Study Area

São Paulo ranks the 4th most populated city in the World (UNITED NATIONS, 2018). Located in the Southeast region of the State of São Paulo, Brazil, it has an area of 1.5 million km². São Paulo City generates, on average, 20 thousand tons of solid waste daily, including household, health care, free market, green waste, road cleaning, commercial and construction and demolition waste. The household waste represents 60% of the total, or around 12 thousand tons/day (PMSP, 2018).

The present work was limited to gathering data on the household collection service of the Southeast region of the São Paulo City (Figure 1), which has about 6.7 million inhabitants in an area of 989.86 km². This region has 54% of the household waste generated by the city (on average, 6,500 t/day) (PMSP, 2018). The city has a Solid Waste Integrated Management Plan that mentions the implementation of new treatment units, as well a public orientation for change the existing model where sanitary landfill prevails (PMSP, 2014).

Figure 1. São Paulo City - Southeast region location.



2.2 Gravimetry

The gravimetric data used was obtained from the characterization campaigns carried out for Southeast region in January, May and September of the years 2017 and 2018. Table 1 presents the values obtained for each gravimetry campaign.

Table 1. The result of the gravimetry campaigns carried out in 2017 and 2018 on the Southeast Region of the São Paulo City.

Materials	**1º Q2017 (%)**	**2º Q2017 (%)**	**3º Q2017 (%)**	**1º Q2018 (%)**	**2º Q2018 (%)**	**3º Q2018 (%)**	**Average (%)**
Organics	48.1	50.6	48.3	45.0	44.5	41.3	46.3
Paper/ Carboard	14.9	10.3	10.4	9.2	11.3	11.1	11.2
Tetrapak	2.1	0.5	0.6	1.3	1.1	0.6	1.0
PET	3.1	0.7	1.0	1.3	0.8	0.8	1.3
PS	0.4	0.3	0.3	0.4	0.4	0.4	0.4
LDPE	7.7	10.8	9.8	9.6	10.4	11.1	9.9
HDPE	6.0	5.6	5.9	3.1	4.6	9.1	5.7
Ferrous	0.1	1.2	1.2	1.6	1.0	1.0	1.0
Glasses	1.2	1.4	2.8	2.3	1.8	1.7	1.9
Inerts	0.9	0.5	0.3	7.0	5.0	3.3	2.8
Wood	1.8	1.8	1.8	3.7	2.7	2.2	2.3
Textile	3.6	6.6	9.6	5.4	4.3	7.3	6.1
Others	0.7	0.6	0.7	0.1	1.3	0.5	1.0
Non-Ferrous	1.2	0.3	0.4	0.4	0.4	0.5	0.5
Rubber	0.2	0.3	0.2	2.8	1.3	0.4	0.9
Foam	0.4	0.6	0.3	0.9	0.5	0.2	0.5
Diapers	7.3	7.4	5.9	5.3	8.2	8.2	7.0
Electronic waste	0.0	0.0	0.0	0.2	0.0	0.2	0.1

With the exception of organic matter, paper, soft plastic and diapers, the other materials present a greater dispersion, which demonstrates the great heterogeneity of MSW and the complexity that this characteristic imposes in large scale waste treatment projects.

2.3. Mass Balance for Mechanical Treatment

Based on the process in operation in the mechanical Material Recovery Facilities (MRFs) in the São Paulo City and the survey of technical equipment's data, a mechanical treatment process was prepared to obtain the necessary parameters to suggest scenarios closer to the real.

In order to obtain a greater materials recovery, was considered the sorting of: glass; paper/cardboard; soft plastic or light density polyethylene (LDPE); high density polyethylene (HDPE); polyethylene terephthalate (PET); polypropylene (PP); Tetrapak; recovery derived fuel (RDF) and organic matter.

The mechanical sorting model aims to produce recyclable materials and RDFs, varying according to the waste input.

The processes used in the proposed model of MSW sorting plant involve elements such as: high technology gravity sorting sieves (trommel); ballistic separators, that split the waste by its dimensions (2D and 3D); optical sensors, that perform spectral analysis for distinguishing the types of plastics according to the polymers present in its composition or by types of fibrous materials such as paper or cardboard. And finally, magnetic (ferrous) and induction separators (non-ferrous) for sorting ferrous and non-ferrous materials.

After sorting, all materials are sent by different conveyors to a cabin, where environmental agents proceed a manual quality control, guaranteeing the purity of the segregated products.

2.4. Criteria Definition

According to the composition of the MCDM mentioned techniques (AHP and TOPSIS) in Introduction, the best alternative would be the one that is closest to the positive ideal solution and the one that is farthest from the negative ideal solution. The positive ideal solution is the one that maximizes the benefit criteria and minimizes the cost criteria; while the negative ideal solution maximizes the cost criteria and minimizes the benefit criteria.

Authors such as Pires, et al. (2011); Generowicz, et al. (2011); Maghajani Mir, et al. (2016), Vucijak, et al. (2016), Coban et al. (2018) and Ali, et al. (2018) related four main criteria in the decision process, like: environmental, technical, social and economic.

The Table 2 presents the calculation methodology attributed to each criterion, but first it is important to mention the average daily amounts of the waste collected, destined to the sorting plants or disposed into the landfills. The data provided by the company that executes the household waste collection, treatment and sanitary landfill final disposal in the Southeast region presented an average of 6,635.43t/day collected by mixed waste collection and 132.81t/day of selective waste collection in the study period, representing respectively 98% and 2% of the total amount collected (Ecourbis Ambiental, 2019).

Table 2. Calculation methodology attributed to each considered criterion.

	Criterion	Methodology
Environmental	C1 – Recovery of raw materials (t/day)	In the scenario raised in 2019, there were no precise data regarding the efficiency rate of the Southeast region, which at the time comprised oneMRF and 20 manual sorting cooperatives. Interviews conducted with manual cooperative leaders reported that the refuse rate at those facilities was about 40% (Cooperativas, 2019). For the MRF is equivalent, about 39%, adopted as recovery rate in the study (Ecourbis Ambiental, 2019). The adopt model used the daily average of the refuse weight at the sorting process output, in relation to the daily average of waste that entered at the facility.
	C2 - Reduction of landfilled biodegradable MSW (t/day)	Relevant environmental indicator, since its implementation, besides avoiding possible fugitive methane emissions and soil contamination, reducing the leachate generation, which are high concerns of the sanitary landfills.
	C3 - Emissions to the environment	For the calculation of this criteria, the method for calculating the "zero waste" index, proposed by Zaman and Lehmann (2013), was used. The methodology developed calculates the amount of air emissions avoided through the return of the post-consumers materials to the production chain, or in the waste treatment flow.
	C4 - Landfill Diversion Rate (%)	Amount of waste that is diverted from the landfill in relation to the total disposed in the baseline scenario.
Economic	C5 - Annual operational costs (monetary units)	Studies conducted by the World Bank (2018), Ghinea and Gavrilescu (2016) and Kasa and Bhada-Tata (2018) presented the operational costs of solid waste treatment technologies currently used in several countries. For this criterion was adopted the average value of each technology, among the studies mentioned, which are: Landfill US$45/t; Mechanical Treatment US$30.9/t; Composting US$62.5/t; Anaerobic Digestion US$65.8/t; and Incineration with energy recovery US$119.6/t.
	C6 - Income from sailed recyclables/ RDF (monetary units)	Current sellers of RDF in São Paulo State related the price equivalent to delivery at the cement plant's door. Cooperatives in the São Paulo City, and suppliers of waste treatment equipment contributed with the values currently practiced for sale the recyclables and the electricity generated through the waste treatment.
	C7 – Energy Production (MWh/year)	The results obtained by Abrantes (2016) were adopted as reference for calculating the energy performance of the thermal treatment unit. The energy generation by methanization and its products was calculated through the study performed by Favoino et al. (2013) and Colturato (2018).
Social	C8 - Employment (number of new employees)	The adopted values, collected through interviews in waste treatment units located in Brazil and Europe, were: 90 employees for a mechanical treatment of 1,250t/day, 57 employees for the biological treatment of the organic fraction separated by MBT and about 15 employees for each 1,600t/day of thermal treatment by incineration.
	C9 - Reaching the objectives of the national Waste Management Polices (scale 0-5)	Regarding the waste hierarchy, in which non-generation is the best option and landfill disposal is the worst option, the concept was assigned from 1 to 5 in scale for each scenario, being 1 for low attendance and 5 for total attendance.
	C10 - Social acceptance (scale 1-5)	Subjective criterion, referring to the society's level of acceptance of certain waste treatment facilities. In the study case, technologies that apply sorting for recycling have better acceptance than those for energy recovery through incineration. Thus, was assigned from 1 to 5 in scale for each scenario, being 1 for lower acceptance and 5 total acceptance.
Technical	C11 - Length of time required for the introduction of the scenario (year)	Estimated time for complete scenario start.
	C12 – Employee Qualification (scale 0-100)	For this criterion, the values applied in the study by Coban et al. (2018) were adopted, which mentions the workforce qualification level for each treatment technology. In this study, after survey, a scale from 0 to 100, where 0 does not require any qualification and 100, high qualification level.
	C13 – Space Availability (scale 1-5)	Considering the literature review, a concept of 1 to 5 was assigned to the area required in each scenario. Thus, 1 was assigned to the scenario that in relation to the amount of waste treated requires a smaller area and a scale up to 5, for a scenario that required a larger area.

2.5. Weights definition – AHP Method

Mathematical formulations of AHP method are carried out as follows (Saaty, 1980; Ali et al., 2018):

i. First of all, decompose the decision problem into an hierarchy, with a goal at the top and levels of criteria and decisions defined;

ii. Develop a decision matrix using Saaty's nine-point priority scale. The decision matrix measures each alternative to the multiple decision criteria. The rating scale suggested by Saaty (1980) is based on the values from 1 to 9 for assessing the comparative weight of every variable with other through the pair-wise diagonal matrix. The smallest value, i.e., 1, depicts the importance of both parameters, whereas 9 depicts dominantly important. In this study, the power of significance among two variables is filed in a matrix using knowledge and field specialist's opinion (Table 3). If a decision problem has n criteria and m alternatives, the decision matrix will be as follows:

$$P = \begin{bmatrix} d_{11} & \cdots & d_{1n} \\ \vdots & \ddots & \vdots \\ d_{n1} & \cdots & d_{nn} \end{bmatrix} \quad (1)$$

If the second alternative is preferred over the first, the reciprocal of the rating is given.

iii. The comparison pairs of the hierarchy are constructed. The relative priority is calculated with respect to each element. The pairwise comparison is represented as:

$$\begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} = \begin{bmatrix} {}^{w_1}/_{w_1} & {}^{w_1}/_{w_2} & \cdots & {}^{w_1}/_{w_n} \\ {}^{w_2}/_{w_1} & {}^{w_2}/_{w_2} & \cdots & {}^{w_2}/_{w_n} \\ \vdots & \vdots & \vdots & \vdots \\ {}^{w_n}/_{w_1} & {}^{w_n}/_{w_2} & \cdots & {}^{w_n}/_{w_n} \end{bmatrix} \quad (2)$$

$n(n - 1)/2$ comparisons are consistent, where n is the number of the criterion; then, elements $\{a_{ij}\}$ will fulfill the following conditions: $a_{ij} = w_i/w_j = 1/a_{ij}$ and $a_{ii} = 1$ with $i, j, k = 1, 2, \dots. n$.

iv. Normalize the matrices. This is performed by dividing each column by the sum of the numbers in the corresponding column. The sum of the elements of each column in the normalized matrix must be equal to one.

v. The determination of the “W” contribution of each criterion in the organizational goal is calculated from the priority vector or Eigen vector. The Eigen vector presents the relative weights between the criterion and is obtained approximately, through the arithmetic average of the values on each row in the normalized matrix. The values found for the Eigen vector have direct physical significance on the AHP. It determines the share or weight of that criteria in the total goal result.

2.6. TOPSIS method

Mathematical formulations of TOPSIS method are carried out as follows (Maghajani Mir, et al., 2016; Tzeng & Huang, 2011):

vi. First of all, formulate an input decision matrix for the ranking comprising all criteria and alternatives. TOPSIS method uses all outcomes (x_{ij}) of a decision matrix to develop a compromise rank. The viable alternatives of the decision process are $A1, A2, ., An$. The structure of the input decision matrix is denoted by $X = (x_{ij})_{nxm}$, where, x_{ij} is the outcome of i^{th} alternative with respect to j^{th} criterion. $W = (w_{1,} w_2, \dots, w_j, \dots w_m)$ is the relative weight vector about the criterion, and w_j represents the weight of the j^{th} attribute and $\sum_{j=1}^{m} w_j = 1$.

vii. Normalize the input decision matrix using the following equation:

$$\overline{X_{ıȷ}} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{n} x_{ij}^2}} \tag{3}$$

where $\overline{X_{ıȷ}}$ is the normalized value of X_{ij} and j=1.... n

viii. Weighted normalized decision matrix is calculated by multiplying the normalized decision matrix by its associated weights obtained from the AHP weights as:

$$V_{ij} = W_j * \overline{X_{\imath\jmath}} \tag{4}$$

ix. Identify the Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS), respectively, as follow:

$$PIS = A^{+} = \{V_1^{+}, \cdots V_j^{+}, \cdots V_n^{+}\} = \{(max_j V_{ij} | j = 1, \cdots, n) | i = 1, \cdots, m\} \tag{5}$$

$$NIS = A^{-} = \{V_1^{-}, \cdots V_j^{-}, \cdots V_n^{-}\} = \{(min_j V_{ij} | j = 1, \cdots, n) | i = 1, \cdots, m\} \tag{6}$$

x. Determine the Euclidean distance of each of alternatives from the PIS and NIS, respectively:

$$d^{+} = \sqrt{\textstyle\sum_{j=1}^{n} W_j \left(V_{ij} - V_j^{+}\right)^2} \cdots\cdots d^{-} = \sqrt{\textstyle\sum_{j=1}^{n} W_j \left(V_{ij} - V_j^{-}\right)^2} \tag{7}$$

xi. Calculate the relative closeness of the i^{th} alternative to the ideal solution using the following equation:

$$\xi_i = \frac{d_i^{-}}{d_i^{-} + d_i^{+}} \tag{8}$$

xii. By comparing $\xi_i$values, the ranking of alternatives is determined. Higher $\xi_i$value means the best is the rank.

Finally, rank the alternatives starting from the value that closest to 1 and in decreasing order.

3. RESULTS AND DISCUSSION

3.1. Mechanical Treatment's Mass Balance

The strategy for good mechanical sorting is to extract as many non-valuable materials as possible at the beginning of the process and to allow a lower flow through the sorting equipment, increasing the efficiency of the process as a whole (Christensen, 2011; Pognani et al., 2012). As an example, at the mechanical sorting beginning stage is necessary sorting the materials that have a high proportion of organic matter, textiles and diapers, which, as presented in Table 1, represent about 60% of the waste mass. Thus, their separation will simplify the following stages of the mechanical process, since the volume of waste will be lower.

The Figure 2 presents the whole process applied in the model, with the respective sorting rates of each step. At the beginning, after entering the mechanical sorting unit, waste pass through a bag opener machine and then go to the first sorting cabin to remove larger materials, those could damage equipment in the following stages. Among this manually sorted materials are recyclables (products) / RDF and rejects, those represent approximately 1.3 % of the input amount.

After the first cabin, waste goes to the rotary sieve (trommel), where it is separated into fractions according to its size: the fraction denominated 1 is the material with granulometry below 90 mm (fines), fraction 2 is the material with granulometry between 90 mm and 280 mm and fraction 3 is the material with granulometry above 280 mm.

The three fractions separated by the trommel go to different parts of the process. Fines (<90mm), which contains predominantly organics, goes to organic treatment, the medium fraction (90-280 mm) goes to ballistics and the bulk materials go to a manual sorting cabin.

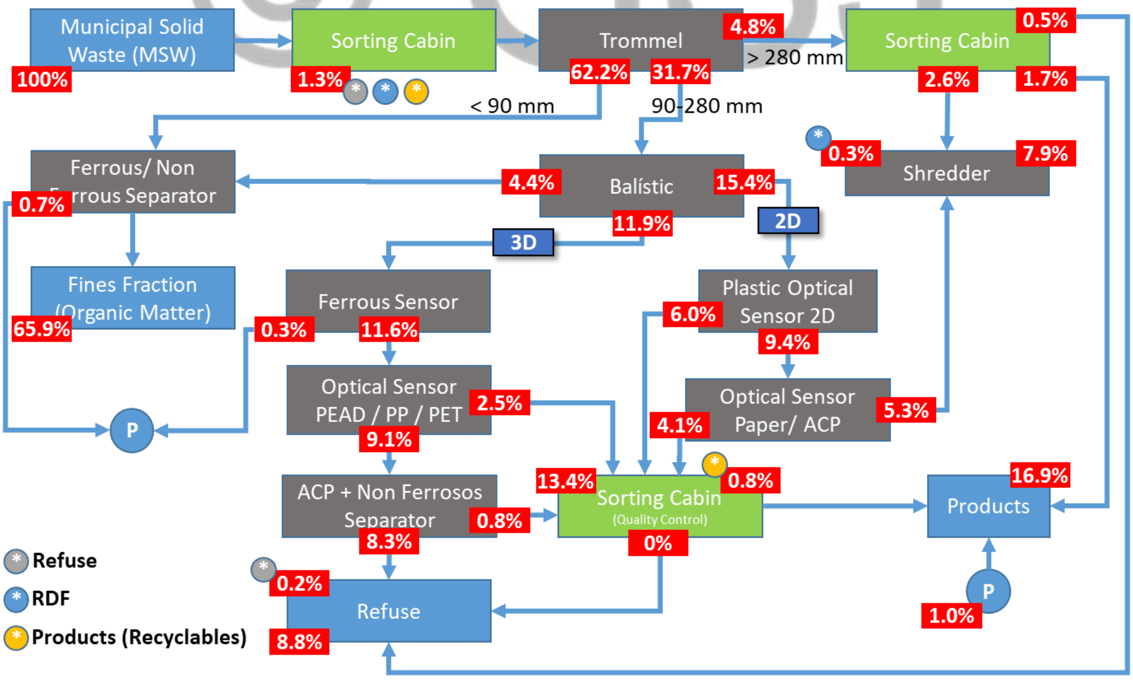
The proposed model shown that the fines fraction (< 90 mm) presents the major proportion of segregated materials, reaching about 65.9% of the input waste, containing inert materials such as glass, sand and plastics, beyond organics. It is important to note that the gravimetric characterization in the studied period (2017-2018) presented 46.6% of organic matter, the difference is considered reject.

The ballistic equipment sorts the materials according to their shape (medium fraction). Flat materials (2D) are thrown to the top of the equipment, due to the movement of its internal, inclined and perforated surface. Three dimensions (3D) materials drop to the internal agitation to the lower part of the equipment and the fines are separated during the agitation through the perforated agitation surface. The manufacturers consider that the desired efficiency is achieved by varying the inclination of the equipment internal surface, so when the input waste has a greater amount of 3D materials, the inclination is increased, while a greater amount of flat materials (2D) allows a lower inclination.

The sorting phase of the fraction above 280mm has the objective to separate materials that can damage shredders or recyclables, such as large plastic films and cardboard boxes. In the proposed model, this phase segregates 2.2 % of the input waste.

The 2D materials, separated by the ballistic equipment, are transferred to a first optical sensor, where light plastics are segregated. A second optical sensor ejects paper, cardboard and crumpled Tetrapak. The non-ejected materials are sent to the crushing line for use as RDF. After pass through the optical sensors, materials go to a cabin for a manual quality control and then to the accumulation bays for subsequent pressing and recycling.

Figure 2. Complete mechanical separation flow, based on the MRF model that operates in the Southeast region, São Paulo City.



3.2. Proposed Scenarios for Integrated MSW Management

Five scenarios were proposed for the study area, considering the real applicability of these technologies according to the local policies and interests, presented in Table 3.

Table 3. Scenarios definition for the integrated MSW management, considering the real practice of the Southeast Region of the São Paulo City.

Scenario	Considerations
1	Considers the current model practiced in the Southeast Region, where 98% of the solid waste collected is sent directly to the landfill and the remaining 2% is selective collected by households. Despite the 2% collected, only 1.2% is effectively relayed to the recycling industry. The cooperatives and MRF receive the selective waste, sort a part and the remaining (process refuse) is collected by the municipal waste collection and sent to the landfill, thus the landfill receives 98.9% of the waste generated in the Southeast Region.
2	Maintains the selective collection in 2 % and adds 2 MBT plants, each one with 1,250 t/day of capacity, as recommended by PMS (2014). The dry fraction will be commercialized as RDF or as recovered products, such as plastic and cardboard. In this case, the amount of waste disposed into the landfill would be 64.4 % of the total amount of MSW generated, around 1,000 t/day of composted material would be produced to cover green areas and the recycling rate would increase to 7.4 %.
3	Considers an increase of 150 % in the current selective collection and adds 2 waste to energy (WtE) recovery plants, each one with 2,700 t/day of capacity. In this case, the amount of waste disposed into the landfill would be 28.6 % of the total amount of MSW generated and the recycling rate would increase to 3.0 %.
4	Considers the current amount of selective collection (2%), 2 MBT plants of the Scenario "2" and 2 WtE plants, each one with 1,800 t/day of capacity. The sum of the energy generated among the methanization process (823 MWh/day) and WtE (1,577 MWh/day) will be 2,400 MWh/day. In this case, the amount of waste disposed into the landfill would be 19.2 % of the total amount of MSW generated
5	Considers the hypothesis of the Scenario "4", but do not find destination for the treated organic materials, implying their final disposal into the landfill. In this case, the amount of waste disposed into the landfill would be 34.0 % of the total amount of MSW generated

It should be noted that these scenarios were chosen based on the experience of the municipal MSW management in São Paulo City, whose difficulty in increasing selective collection is due to the scarcity of continuous efforts to raise environmental awareness among the population and the great informal market by the cooperatives, whom sale the recyclable materials. These factors imply in a great materials market seasonality throughout the year, limiting the market growth and, consequently, the demand for these products by the industries, because there no interest in trading products with a low market price (e.g. at the end of the year there is no interest in cardboard sorting because at this time the price of the packaging is low).

3.3. Criteria Weights According to the AHP Method

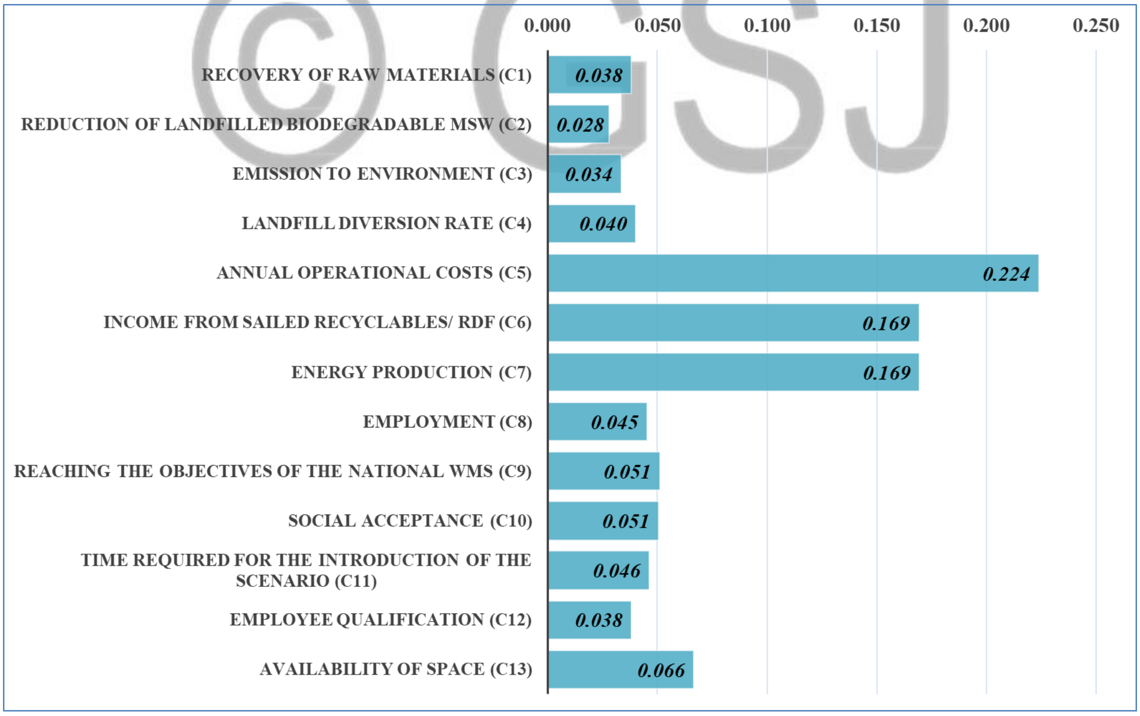
According to the item 2.5, the criteria were compared in pairs, in accordance with the fundamental scale, and organized. Table 4 presents the results of the comparisons.

Table 4. Results of the criteria comparisons using the AHP method.

Criteria		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
Recovery of raw materials	C1	1.00	1.00	1.00	1.00	0.14	0.20	0.25	1.00	1.00	1.00	0.50	3.00	0,33
Reduction of landfilled biodegradable MSW	C2	1.00	1.00	0.50	0.50	0.14	0.17	0.25	0.50	0.50	0.50	0.50	2.00	0,50
Emission to environment	C3	1.00	2.00	1.00	1.00	0.20	0.20	0.33	1.00	1.00	1.00	0.25	0.25	0.25
Landfill Diversion Rate	C4	1.00	2.00	1.00	1.00	0.14	0.20	0.20	1.00	1.00	1.00	0.33	3.00	0.50
Annual operational costs	C5	7.00	7.00	5.00	7.00	1.00	0.50	3.00	5.00	7.00	7.00	7.00	2.00	4.00
Income from sailed recyclables/ RDF	C6	5.00	6.00	5.00	5.00	2.00	1.00	0.33	4.00	3.00	6.00	6.00	4.00	1.00
Energy Production	C7	4.00	4.00	3.00	5.00	0.33	3.00	1.00	5.00	3.00	5.00	5.00	3.00	4.00
Employment	C8	1.00	2.00	1.00	1.00	0.20	0.25	0.20	1.00	1.00	1.00	2.00	2.00	1.00
Reaching the objectives of the national WMS	C9	1.00	2.00	1.00	1.00	0.14	0.33	0.33	1.00	1.00	1.00	2.00	2.00	2.00
Social acceptance	C10	1..00	2.00	1.00	1.00	0.14	0.17	0.20	1.00	1.00	1.00	2.00	3.00	2.00
Length of time required for the introduction of the scenario	C11	2.00	2.00	4.00	3.03	0..14	0.17	0.20	0.50	0.50	0.50	1.00	1.00	0.50
Employee Qualification	C12	0.33	0.50	4.00	0.33	0.50	0.25	0.33	0.50	0.50	0.33	1.00	1.00	0.50
Availability of space	C13	3.03	2.00	4.00	2.00	0.25	1.00	0.25	1.00	0.50	0.50	2.00	2.00	1.00
Total		28.4	33.5	31.5	28.9	5.3	7.4	6.9	22.5	21.0	25.8	29.6	28.3	17.6

After adopt the procedures mentioned at steps “iv” and ‘v” of the item 2.5, the “W” value contribution for each criterion is presented in Figure 3.

Figure 3. Complete mechanical separation flow, based on the MRF model that operates in the Southeast region, São Paulo City.



The results above indicate the greater weight given to the economic criteria, followed by social, technical and environmental criteria, respectively. About the technical criteria, the area for construction reached the higher position than the others, due to the difficulty to find available areas for this purpose in the São Paulo City.

3.4. TOPSIS Method for Determining the Scenario Closest to Ideal

The Table 5 presents the results of the environmental, economic, social and technical criteria, according to the assessment criteria mentioned in Table 2.

Table 5. Criteria assessment for the different scenarios.

Scenario	(C1)	(C2)	(C3)	(C4)	(C5)	(C6)	(C7)	(C8)	(C9)	(C10)	(C11)	(C12)	(C13)
1	81.01	0	-5.282	1.22	93.16	35.64	0	0	1	1	0	10	5
2	709.01	1157.5	-2.374	35.58	138.40	193.78	823.50	147	3	4	2	40	4
3	202.53	2500.2	486	71.40	246.55	89.11	2634.35	60	2	2	3	80	2
4	709.01	2824.3	1.310	80.64	241.83	193.78	2400	162	4	3	3	80	3
5	709.01	2824.3	1.310	65.93	241.83	193.78	2400	162	4	3	3	80	3

The comparison between Scenarios 4 and 5, regarding environmental criteria, is established in the Table 5 by the amount of waste diverted of the landfill. In relation to emissions, these two scenarios are equivalent, because even the compost being sent to the landfill, there is no longer the presence of organic matter.

It is clear that the operational costs related to the landfill are lower than any other treatment technology, which is shown in the Table 5 for C5.

The Table 5 also presents the results attributed to the legislation criteria for each scenario, which considered that only waste that could be disposed into the landfill is reject, thus the waste disposal in landfill directly, without any treatment, received the lowest value (C9). In Scenario 3, the energy recovery with low increase in recycling recovery is not ideal either, so it also obtained a low value (C9). The Scenario 4, that implements concomitantly an increase in the recyclables and the energy recovery, establishes a solution closer to the ideal, but it did not obtain a maximum score due this scenario do not yet obtain a large amount of materials recovery compared to the total waste generated by the Southeast region.

The landfill public acceptance is only lower than the thermal treatment through incineration (Scenarios 1 and 3 for C10), while a solution that presents an integration of technologies has better acceptance (World Bank, 2018).

It was considered "0" for the landfill implementation time (C11), since the MSW is currently disposed in an existent landfill, in Scenario 1.

The Table 6 presents the "V_{ij}" values, resulted after procedures mentioned at steps “vii” and ‘viii” of the item 2.6, as also the “PIS” and “NIS” values mentioned at step “ix”.

Table 6. Weighted normalized decision matrix

Scenario	(C1)	(C2)	(C3)	(C4)	(C5)	(C6)	(C7)	(C8)	(C9)	(C10)	(C11)	(C12)	(C13)
1	0,002	0,000	-0,029	0,000	0,046	0,017	0,000	0,000	0,008	0,008	0,000	0,003	0,042
2	0,022	0,007	-0,013	0,011	0,068	0,094	0,032	0,024	0,023	0,032	0,017	0,011	0,033
3	0,006	0,014	0,003	0,022	0,122	0,043	0,102	0,010	0,015	0,016	0,025	0,021	0,017
4	0,022	0,016	0,007	0,025	0,119	0,094	0,093	0,026	0,030	0,024	0,025	0,021	0,025
5	0,022	0,016	0,007	0,020	0,119	0,094	0,093	0,026	0,030	0,024	0,025	0,021	0,025
PIS	0,022	0,016	0,007	0,025	0,046	0,094	0,102	0,026	0,030	0,032	0,000	0,003	0,017
NIS	0,002	0,000	-0,029	0,000	0,122	0,017	0,000	0,000	0,008	0,008	0,025	0,021	0,042

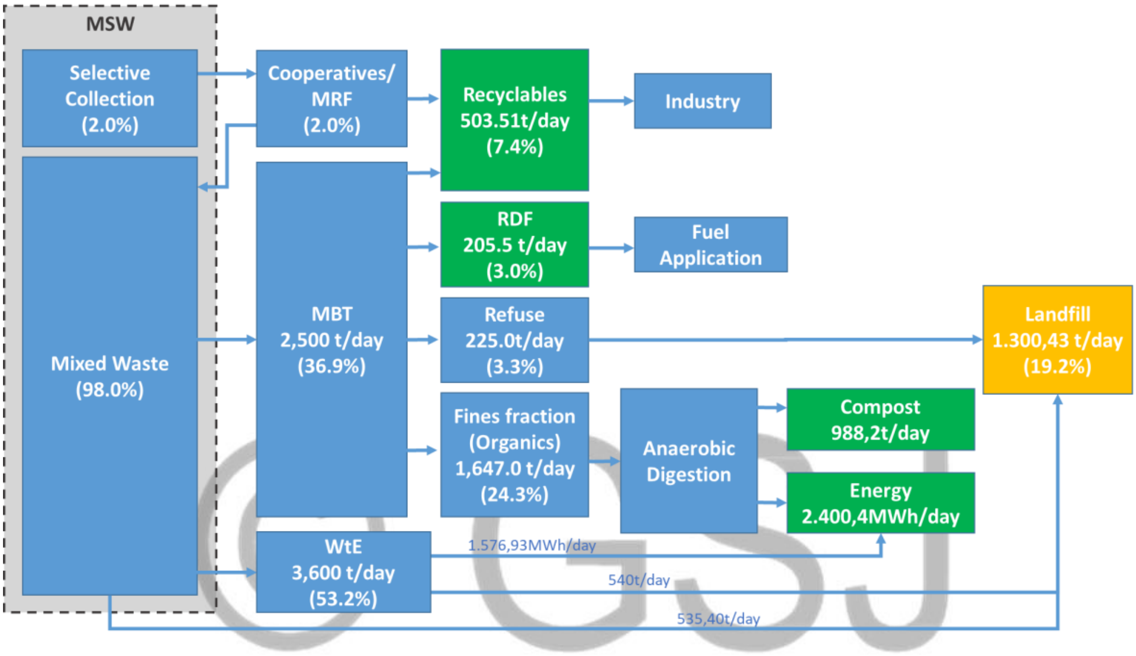
The Table 7 presents the TOPSIS method results, after the application of the calculation step "x" of the item 2.6. The scenarios were ordered according to their proximity to the ideal solution.

Table 7. TOPSIS method result for the study case.

Scenario	d^+	d^-	ξ_i	Rank
1	0.1457	0.0818	0.3597	5
2	0.0824	0.1102	0.5722	3
3	0.1015	0.1167	0.5347	4
4	0.0811	0.1371	0.6284	1
5	0.0812	0.1364	0.6268	2

The results presented in the Table 7 ranks the scenarios in relation to the closest to ideal solution where, for the evaluated criteria, Scenario 4, detailed in Figure 4, is the best among the proposed ones. The Scenario 3, which proposes basicaly only incineration as a technological route, stayed in the fourth position, in front of the scenario that disposes of all the waste amount in landfill, but behind Scenario 2, which aggregates the technologies of sorting and biological treatment. The scenarios proposed did not consider the landfill's useful life, as well as any need for future investments in the current landfill or the need to change the current waste disposal logistics, which would increase operational costs.

Figure 4. Proposed Flowchart for Scenario 4, ideal solution found for the Southeast Region of the São Paulo City.



4. CONCLUSIONS

The gravimetric data identified that, with exception of the organic matter, presented significant variation between the analyses carried in 2017 and 2018, which evidences the inherent challenge of the MSW characterization for different treatment techniques in large scale.

The model of mechanical recovery showed that the fraction of fines, mostly formed by organic waste, goes to biological treatments with an important portion of impurities, that impairs the quality of the compost, causing a possible problem to sell it.

For this case study, the best scenario proposed using the TOPSIS method calculation was Scenario 4, which applies an integration of different technological routes, including selective collection, biological mechanical treatment and thermal treatment by incineration, since it contributes to the recovery of materials and, consequently, to the circular economy, besides producing an important amount of energy, as well as reduce the landfill waste disposal. The Scenario 4 implementation introduces MBT units and thermal process with energy recovery in São Paulo City, raising the selective collection, what resulted in an estimated reduction of 80.2% in final landfill disposal. The scenario that has thermal treatment as the mainly solution, despite the large volume treated and energy produced, as function of operating costs and recyclables recovery rate, left it in the second to last position. The current scenario, which the most part goes to the landfill disposal is the farthest from ideal. When thermal treatment with energy recovery is added to other technologies, which incorporate material recovery, they make the scenarios more attractive as evidenced by the position of scenarios 4 and 5, which reached the first and second position, respectively.

The treatment steps listed as the better scenario for the Southeast Region of the São Paulo City, which include mechanical sorting, biological treatment, thermal treatment and selective collection, are necessary parts of and adequate and sustainable integrated MSW management in large demographic concentrations, if not open dumps in developing countries, where landfills will become increasingly scarce and more distant, implying higher logistical costs.

The migration from a model based on the prevailing use of landfills to models aimed at materials and energy recovery should be sought to meet the waste treatment hierarchy provided in the international legislation and thus increase the products' life cycle.

Acknowledgements

This work has been supported by Ecourbis Ambiental S.A., that became possible several technical visits in municipal waste treatment plants, as also the availability data from the

gravimetric studies. This research is also approved by CNPq (National Council for Scientific and Technological Development).

References

Abrantes, J. M. (2016). Avaliação técnica e económica da aplicação de sistemas Waste to Energy no tratamento de resíduos urbanos em aglomerados de média e pequena dimensão. Instituto Técnico de Lisboa.

ALI, Y., ASLAM, Z., DAR, H., & MUMTAZ, U. (2018). A multi-criteria decision analysis of solid waste treatment options in Pakistan: Lahore City - a case in point. *Environment Systems and Decisions*.

Antonopoulos, I. S., Perkoulidis, G., Logothetis, D., & Karkanias, C. (2014). Ranking municipal solid waste treatment alternatives consideringsustainability criteria using the analytical hierarchical process tool. *Resources, Conservation and Recycling 86*, pp. 149-159.

Borgatto, A., Rizzo, R., & Mahler, C. (2007). Utilization of the Germany Recomendation E1-7 GDA in the classification of MSW from Rio de Janeiro.

Christensen, T. H. (2011). *Solid Waste Technology & Management* (1º ed.). Chichester: John Wiley & Sons.

Coban, A., Ertis, E. F., & Cavdaroglu, N. A. (2018). Municipal solid waste management via multi-criteria decigion making methods: A case study in Istambul, Turkey. *Journal of Cleaner Production 180*, pp. 159-167.

Colturato, L. (2018). Capacitação sobre a Nota Técnica nº 164/2018-MP - Diretrizes à estruturação de projetos relacionados ao manejo dos resíduos sólidos urbanos (RSU) no âmbito do FEP. Ministério das Cidades/ FUNASA.

Cooperativas. (2019). Entrevistas com Lideres de Cooperativas.

Ecourbis Ambiental. (2019). *Ecourbis Ambiental S.A.* Acesso em 8 de Novembro de 2019, disponível em Entrevista com os Diretores.

Favoino, E., Confalonieri, A., & Boyer, F. (2013). Development of Legal Framework on Bio-Waste Management and Establishment of Quality Assurance System for Compost and National Organisation of Quality Assurance for the Compost. European regional development fund.

Generowicz, A., Kowalski, Z., & Kulczycka, J. (2011). Planning of Waste Management Systems in Urban Area Using Multi-criteria Analysis. *Journal of Environmental Protection 2*, pp. 736-743.

Ghinea, C., & Gavrilescu, M. (2016). Costs Analysis of Municipal Solid Waste management Scenarios: IASI - Romania Case Study. *Journal of environmental engineering and landscape management 24*, pp. 185-199.

Kasa, S., & Bhada-Tata, P. (2018). *Decision Maker's Guides for Solid Waste Management Technogies.* International Bank for reconstruction and Development, Washington.

Lisa, D., & Anders, L. (2008). Methods for household waste composition studis. *Waste Management 28*, pp. 1100-1112.

MAGHAJANI MIR, M., GHAZVINEI, P., SULAIMANAN, M., BASRI, N., SAHERI, S., N.Z., D., . . . AGHAMOHAMMADI, N. (2016). Application of TOPSIS and Vikor improved versions in a multi criteria decision analysis to develop an optimized municipal solid waste management model. *Journal of Environmental Management 166*, pp. 109-115.

Pires, A., Chang, N. B., & Martinho, G. (2011). An AHP-based fuzzy interval TOPSIS assessment for sustainable expansion of the solid waste management system in Setúbal Peninsula, Portugal. *Resources, Conservation and Recycling 56*, pp. 7-21.

PMSP. Prefeitura Municipal de São Paulo. Plano de Gestão Integrada de resíduos Sólidos da cidade de São Paulo, 2014. Disponivel em: <http://www.prefeitura.sp.gov.br/cidade/secretarias/upload/servicos/conferencia_meio_ambiente/arquivos/PGIRS_geral.pdf>. Acesso em: 18 Julho 2018.

PMSP. *Prefeitura do Municipio de São Paulo*. Acesso em 01 de Outubro de 2018, disponível em AMLURB: https://www.prefeitura.sp.gov.br/cidade/secretarias/subprefeituras/amlurb/coleta_seletiva//index.php?p=229723

Pognani, M., Barrena, R., Font, X., & Sánchez, A. (2012). A complete mass balance of a complex combined anaerobic/aerobic municipal. *Waste Management 32*, pp. 799-805.

Rszkowska, E. (2011). Multi-criteria decision making models by applying the topsis method to crisp and interval data. *Computer Science*.

Saaty, T. L. (1980). *The Analytic Hierarchy Process*. Nova Iorque: McGraw Hill.

Saaty, T. L. (1994). How to make a decision: the analytic hierarchy process. *Vol 24 Nº 6*, pp. 19-43.

Tzeng, G. H., & Huang, J. J. (2011). *Multiple Attribute Decision making Methods and Applications*. Flórida: Taylor e Francis Group.

UNITED NATIONS. Revision of World Urbanization Prospects. United Nations Department of Economic and Social Affairs. [S.l.]. 2018.

Vucijak, B., Kurtagic, S. M., & Silajdzic, I. (2016). Multicriteria decision making in selecting best solid waste management scenario: a municipal case study from Bosnia and Herzegovina. *Journal of Cleaner Production 130*, pp. 166-174.

World Bank. (2018). Municipal Solid Waste Management a road map for reform for policy makers. World Bank.

Zaman, A. U., & Laehmann, S. (2013). The zero waste index: a performance measurement tool for waste management systems in a ‘zero waste city’. *Journal of Cleaner Production 50*, pp. 123-132.