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Multi-criteria analysis for the selection of the best energy efficient option in urban water systems

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Abstract

This paper presents the application of multi-criteria decision analysis to select the best energy efficient option for a water supply system. The case study is a part of the Multi-Municipal Water Supply System (MMWSS) for the Algarve region in Portugal. There is a micro-hydropower plant installed in one of the two water treatment plants. The system has two operating schemes due to the seasonality of tourism: one for the high season from June to September; and the other one for the low season from October to May. The aim of the analysis is to compare the energy efficiency of the system for the two operating schemes and for different demands. Energy audits (i.e., hydraulic energy balance along the pipe system) are carried out for each option (pair operating scheme – demand). Different energy efficiency metrics are calculated and two different multi-criteria analysis methods are used and compared to rank the options. Results obtained are discussed and the main conclusions are presented.

Keywords: Energy efficiency, Energy audit, Greenhouse gases, Multi-criteria analysis, Urban water systems

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1. Introduction

Energy consumption costs, together with the manpower costs, represent a significant part of operating costs of the water services. Energy efficiency is, therefore, critical for the global economic efficiency of utilities. Additionally, it has an increasing environmental importance in order to reduce emissions of carbon dioxide and other gases that contribute to the greenhouse effect. The implementation of projects aiming at the optimization of water and energy resources as well as costs, by reducing energy losses, reducing peak electric consumption and minimizing the environmental emissions footprint, is, therefore, becoming increasingly more common among water utilities. Assessing the energy efficiency is important to establish priorities of intervention and to monitor the effectiveness of implemented solutions.

The traditional single criteria decision making approach, normally aimed at identifying the option with the lowest cost, is not suitable to handle with the selection of the most efficient option as it does not incorporate the social and environmental concerns for reducing the carbon footprint. The multiplicity of metrics and the complexity of energy planning and energy projects make multi-criteria analysis a valuable tool in the decision-making process (San Cristóbal Mateo, 2012).

The current paper addresses the issue of energy efficiency in water supply systems and compares different operating schemes in terms of water sources. It presents the application of multi-criteria decision analysis to select the best energy efficient option for a water supply service. The analysed case study is a subsystem of the Multi-Municipal Water Supply System (MMWSS) for the Algarve region in Portugal. There is a micro-hydropower plant installed in one of the two water treatment plants of the system. The system has two operating schemes due to the seasonality of tourism: one for the high season from June to September; and the other one for the low season from October to May. The aim of the analysis is to compare the energy efficiency of the system for the two operating schemes and for different demands. Energy audits (i.e., hydraulic energy balance along the pipe system) are carried out for each option (pair operating scheme – demand) (Cabrera et al., 2010; Hernández et al., 2010).

Energy audits require the previous simulation of the hydraulic behavior of the system (Souza et al., 2011a; Souza et al., 2011b). Context and performance indicators can be calculated using the results of the energy audit (e.g., dissipated energy, superfluous energy, available energy), in order to assess the energy efficiency from different points of view (e.g., environmental, financial, social). Different energy efficiency metrics are calculated and two different multi-criteria analysis methods (MCAM) are used and compared to rank the options. Results obtained are discussed and the main conclusions are presented.

<table>
<tr><td rowspan="3">Natural input energy (E_N)</td><td rowspan="6">Total energy input (E_E)</td><td rowspan="4">Energy dissipated-recovered (E_D)</td><td>Friction dissipated energy (E_P)</td></tr>
<tr><td>Outgoing energy through leaks – real Losses (E_L)</td></tr>
<tr><td>Local head losses in valves (E_V)</td></tr>
<tr><td rowspan="3">Shaft input energy (E_B)</td><td>Recovered energy (E_R)</td></tr>
<tr><td rowspan="2">Energy delivered to users (E_U)</td><td>Minimum energy required (E_{min})</td></tr>
<tr><td>Superfluous energy (E_S)</td></tr>
</table>

Fig. 1. Energy balance.

2. Energy auditing and energy balance

The aim of an energy audit is to evaluate how much energy is consumed and to identify measures that can be undertaken to reduce consumption, to use energy more efficiently or to produce energy. Performing energy audits in water supply systems is, therefore, a crucial step to improve its energy efficiency. Energy audits can focus only on a single electrical asset of the system (e.g., a pump) or a set of assets (e.g., a WTP), or they assess the hydraulic energy consumption throughout the whole system. As such, energy audit can be of two main types (Souza et al., 2011a; Souza et al., 2011b): (i) energy audit of system electric equipment; and (ii) hydraulic energy auditing of the whole system. The first type of energy auditing is generally carried out by the utilities. In what concerns the second type, Cabrera et al. (2010) have proposed an energy audit based on the time integration of energy conservation equation applied to a known and controlled volume of water. This energy balance shows that the provided energy (by reservoirs and/or pumps) to the system is equivalent to the energy delivered to the users and the outgoing energy through leaks plus dissipated energy due the friction losses. Souza et al. (2011b) have proposed a novel standardized energy balance for water supply systems as shown in Fig. 1.

3. Multi-criteria decision making methods

3.1. Type of methods

The main purpose of multi-criteria decision analysis is to provide decision aiding tools that help finding solutions for real-world problems, most often, problems having conflicting points of view (Vincke, 1992). The multi-criteria problem is related to the methods and procedures by which the different criteria can be formally involved in the decision process. Generally, these problems fall into multi-attribute (discrete problems) or multi-objective problems (continuous problems). Multi-Criteria Decision Analysis (MCDA) problems can be roughly divided into two main groups, viz. multiple attribute decision-making (MADM) and multiple objective decision-making (MODM) problems. In the MADM problems, the decision-maker must choose from among a finite number of available alternatives characterized by a set of multiple attributes (metrics) (Figueira et al., 2005a).

The methods of MADM can be divided into three main groups (Roy, 1996; Vincke, 1992): (i) methods based on the use of a single synthesizing criterion without incomparability (e.g., simple additive weighting); (ii) methods based on outranking relations with incomparability (e.g., ELECTRE); and (iii) methods based on interactive local judgments with trial-and-error iteration. While the first two groups embody a clear mathematical structure, the third does not use any formalized procedure (Getzner et al., 2002).

3.2. Decision matrix

A MADM problem can be easily expressed in a matrix format. A decision matrix is a $M \times N$ matrix in which each element e_{ij} indicates de performance of alternative a_i when it is evaluate of decision criterion g_j (for $j = 1, 2, \ldots, M$ and $i = 1, 2, \ldots, N$). It is also assumed that the decision-maker has determined the relative importance or weights of the decision criteria (denoted as w_j for $j = 1, 2, \ldots, M$):

$$
\begin{array}{cc}
 & \overbrace{\begin{array}{cccc} g_1 & g_1 & \cdots & g_M \end{array}}^{\textit{criteria}} \\
\textit{alternatives} \left\{ \begin{array}{c} a_1 \\ a_2 \\ \cdots \\ a_N \end{array} \right. & \begin{bmatrix} e_{11} & e_{12} & \cdots & e_{1M} \\ e_{21} & e_{22} & \cdots & e_{2M} \\ & \cdots & \cdots & \cdots \\ e_{N1} & e_{N2} & \cdots & e_{NM} \end{bmatrix} \\
\textit{weights} & \begin{array}{cccc} w_1 & w_2 & \cdots & w_M \end{array}
\end{array} \qquad (1)
$$

In this paper the decision criteria are also called metrics.

3.3. Simple additive weighting

The simple additive weighting (SAW) method also called as weighted sum method (WSM) is one of the best known and widely used methods. In this method, alternatives are ranked based on their weighted sum score (Tzeng and Huang, 2011):

$$V\left(a_i\right) = \sum w_j \cdot g_j\left(a_i\right) \tag{2}$$

where: $V(a_i)$ is the ranking score for alternative a_i; w_j is the weight of criterion j; and $g_j(a_i)$ is the normalized preferred rating of alternative a_i with respect to criterion j.

For commensurable comparison all scales of the criteria need to be normalized and all scales need to have the same preference direction (minimization or maximization) depending on the problem. If the problem is of maximization a higher ranking score $V(a_i)$ means a better alternative and if the problem is of minimization a higher ranking score $V(a_i)$ means a worst alternative. For example, if all criteria represent benefits, then the most preferred alternative is the one with the largest cumulative value $V(a_i)$ (Triantaphyllou and Baig, 2005). Several types of normalization techniques can be used to normalize the scales being the most used ratio normalization.

3.4. ELECTRE III

ELECTRE (ELimination et Choix Traduisant la RÉalité) methods are a family of MCDA techniques developed in France. Since their development, which started in the 1960s, ELECTRE methods have been widely used in many real-world decision problems (e.g. energy, transportation, environmental and water management) and proved to be suitable for situations where at least five decision criteria are involved (Almeida-Dias et al., 2006; Figueira et al., 2005b; Rogers and Bruen, 2000). ELECTRE family includes several methods distinguished by the type of problems involved, such as choice, ranking or sorting. The ELECTRE III method is used to rank alternatives from the best to the worst one. To take into account the imperfect nature of the evaluation of alternatives, ELECTRE III makes use of discrimination thresholds (indifference and preference) resulting in a pseudo-criteria model of preferences (Figueira et al., 2010). To use a true-criteria model such as in SAW, the discrimination thresholds in ELECTRE III method can be considered as equal to zero. The ELECTRE III method starts by a pairwise comparison of each alternative to the remaining one in order to accept, reject, or, more generally, assess the credibility of the assertion “alternative *a* is at least as good as alternative *b*” (Almeida-Dias et al., 2006). This method involves two phases: the construction of one or several outranking relation(s) followed by an exploitation procedure. The outranking relation is built through the following steps (Almeida-Dias et al., 2006; Mousseau et al., 1999):

(i) computation of the partial concordance indices $c_j(a,b)$ and $c_j(b,a)$:

$$c_j\left(a,b\right) = \begin{cases} g_j(a) \le g(b) & \text{then} \quad c_j\left(a,b\right) = 0 \\ g_j(a) > g(b) & \text{then} \quad c_j\left(a,b\right) = 1 \end{cases} \tag{3}$$

$$c_j\left(b,a\right) = \begin{cases} g_j(a) \ge g(b) & \text{then} \quad c_j\left(b,a\right) = 0 \\ g_j(a) < g(b) & \text{then} \quad c_j\left(b,a\right) = 1 \end{cases} \tag{4}$$

(ii) computation of the overall concordance indices $c(a,b)$ and $c(b,a)$;

$$c\left(a,b\right) = \frac{\sum w_j c_j\left(a,b\right)}{\sum w_j} \tag{5}$$

$$c\left(b,a\right)=\frac{\sum w_j c_j\left(b,a\right)}{\sum w_j} \tag{6}$$

(iii) computation of the partial discordance indices $d_j(a,b)$ and $d_j(b,a)$;

$$d_j\left(a,b\right)=\begin{cases} g_j(a)\leq g(b) & \text{then} \quad d_j\left(a,b\right)=1 \\ g_j(a)>g(b) & \text{then} \quad d_j\left(a,b\right)=0 \end{cases} \tag{7}$$

$$d_j\left(b,a\right)=\begin{cases} g_j(a)\geq g(b) & \text{then} \quad d_j\left(b,a\right)=1 \\ g_j(a)<g(b) & \text{then} \quad d_j\left(b,a\right)=0 \end{cases} \tag{8}$$

(iv) computation of the fuzzy outranking relation grounded on the credibility indices $\sigma(a,b)$ and $\sigma(b,a)$;

$$\sigma\left(a,b\right)=c(a,b)\prod_{j\in\overline{F}}\frac{1-d_j\left(a,b\right)}{1-c_j\left(a,b\right)} \quad \text{where} \quad \overline{F}=\left\{j\in F\,|\,d_j\left(a,b\right)>c_j\left(a,b\right)\right\} \tag{9}$$

$$\sigma\left(b,a\right)=c(b,a)\prod_{j\in\overline{F}}\frac{1-d_j\left(b,a\right)}{1-c_j\left(b,a\right)} \quad \text{where} \quad \overline{F}=\left\{j\in F\,|\,d_j\left(b,a\right)>c_j\left(b,a\right)\right\} \tag{10}$$

(v) determination of a λ-cut of the fuzzy relation in order to obtain a crisp outranking relation (Fig.).

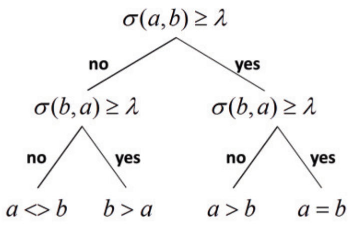

Fig. 2. Outranking relation.

The λ-cut represents the majority of criteria in favour to the assertion "alternative *a* is at least as good as alternative *b*" and therefore it should be always in the interval]0.5; 1.0].

4. Case study

The analyzed case study is a subsystem of the eastbound MMWWS for the Algarve region in Portugal: the Beliche system. The MMWSS supplies about 450,000 inhabitants from October to May and almost triples in the peak of holyday season at summer in which the estimated population is about 1,500,000 inhabitants.

MMWSS has four surface water sources (reservoirs): Odeleite/Beliche; Bravura; Funcho and Odelouca. The Eastbound system is supplied by Beliche/Odeleite reservoir and water is treated in both Tavira and Beliche Water Treatment Plants (WTP). This reservoir aims at irrigation and water consumption uses.

The system has two operating schemes due to the seasonality of tourism: one for the high season from June to September (Fig. 3a); and the other one for the low season from October to May (Fig. 3b). At the low season, only

Tavira WTP is operating and water is conveyed from Beliche to Tavira by a raw water main with 28 km (Fig. 3). At the high season, both Tavira and Beliche WTP's are operating and part of the water is conveyed to Beliche WTP through a 1 km long pipe (Fig. 3). The raw water main from Beliche to Tavira WTP has two pumping stations. At the upstream of Beliche WTP, there is a micro-hydropower plant with two pumps-as-turbine installed. The system downstream Tavira WTP has four pumping stations, four in-line storage tanks and delivers water to 20 municipal tanks as shown in Fig. 3. It is composed of 115 km of pipes with diameters from 40 to 1500 mm.

The aim of this analysis is to compare the energy efficiency of the Eastbound system for two operating schemes:

- Operation Scheme 1 (OS1) – water is treated only in the Tavira WTP; neither Beliche WTP nor the micro-hydro power plant are operating;
- Operation Scheme 2 (OS2) – 78% of water is treated at Tavira WTP and 22% is treated at Beliche WTP; the micro-hydro power plant is operating.

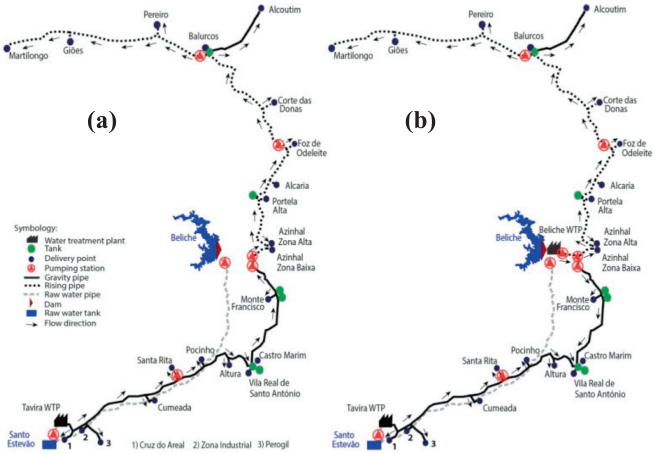

Fig. 3 Operating schemes of the Beliche system at: (a) Winter; (b) Summer.

The hydraulic simulator EPANET was used to assist the calculation of the energy efficiency metrics. The hydraulic model was provided by the water utility. Flow rate data were collected at each delivery point during the year of 2012 and used to calculate delivery water volumes per month. Two representative months were selected: January as a representative month for the low season (LS) and July for the high season (HS). This two demand scenarios were considered for each operation scheme (OS1 and OS2) to assess energy efficiency, and four situations were simulated: OS1-HS, OS2-HS, OS1-LS and OS2-LS.

5. Energy efficiency metrics

Energy in excess per unit of the revenue water (E1) – this index represents the theoretical potential of energy reduction per cubic meter of revenue water. It is always a positive non-zero value, ideally as low as possible.

$$E1 = \frac{E_{exc}}{V_{rev}} \tag{11}$$

where: E_{exc} is the energy in excess (kWh) and V_{rev} is revenue water (m^3).

Ratio of the available energy in excess (E2) - this index quantifies, in a straightforward way, the effective energy in excess that is provided to the system:

$$E2 = \frac{E_E - E_D}{E_{\min}} \tag{12}$$

in which E_E is the total energy input that results from the sum of natural input energy and shaft input energy (kWh); E_D is the total dissipated energy resulting from the sum of dissipated energy in pipes, outgoing energy through leaks and local head losses in valves minus the recovered energy in turbines (kWh); and E_{min} is the minimum energy required by the users (kWh).

Greenhouse gases (GHG) produced from energy use (E3) – this metric intends to determine how much greenhouse gas (GHG) emissions can be reduced by producing electricity through the use of micro-turbines installed in water supply systems and can be determined by Eq. (13).

$$E3 = f_{GHG} \cdot \left(E_S - E_R\right) \tag{13}$$

where $E3$ is GHG produced from energy use (kg CO_2eq); f_{GHG} is a conversion factor (kg CO_2eq/kWh); E_S is shaft input energy from the pumps (kWh) and E_R is recovered energy produced by turbines (kWh).The f_{GHG} estimated by the Portuguese electricity company is of 0.427 kg CO_2eq/kWh.

Energy production profits (E4) – this metric measure the benefit to the water utility by reducing the electric energy purchased from national electric company by consuming the energy produced in the micro-hydro power plant installed in Beliche's WTP. It could be assessed as a ratio between the input shaft energy (E_S) and the recovered energy (E_R):

$$E4 = \frac{E_R}{E_S} \tag{14}$$

Consequence of a failure in Tavira's WTP – this metric intends to measure the impact to the users if a failure that forces the stoppage of Tavira's WTP during an interruption period. This should be a risk metric but since the likelihood of failure due an event that forces a stoppage of a WTP is not easy to estimate, it was decided to assess using a consequence dimension.

Note that Beliche system has two WTP but only Tavira's WTP is considered. The main reason is that if Beliche's WTP fails, full supply to the users is guaranteed from Tavira's WTP. This metric is a ratio between full supply and the percentage of undelivered volume:

$$E5 = 1 - \frac{V_{uns}}{V_{prov}} \tag{15}$$

where $E5$ is the consequence of a failure in Tavra's WTP; V_{uns} is the undelivered volume (m^3) and V_{prov} is the total provided volume to the system (m^3) during the interruption period. The interruption period considered was at least one day.

6. Results and discussion

The results of the variables used to compute the energy efficiency metrics are shown in Table 1.

Table 1. Results of the variables used to compute the energy efficiency metrics

Alternatives	E_{exc} (kWh)	V_{rev} (m^3/h)	E_E (kWh)	E_D (kWh)	E_{min} (kWh)	E_S (kWh)	E_R (kWh)	V_{prov} (m^3)	V_{uns} (m^3)
OS1-HS	314	1,180.8	403.9	280.3	90.3	378.2	–	28,702	0
OS1-LS	158	550.8	201.5	112.0	43.5	189.6	–	13,245	0
OS2-HS	288	1,180.8	389.1	252.3	90.3	364.4	10.7	28,702	14,852
OS2-LS	126	550.8	180.7	99.7	44.2	168.8	10.7	13,245	6,299

Table 2 presents the results obtained of the energy efficiency metrics. The worst values are represented in red and the best values in green, for each metric. The weights were attributed by a panel of technical specialists of the water utility considering three points of view: environmental (E1, E2 and E3), financial (E4) and social (E5).

Table 2. Results of the energy efficiency metrics (decision matrix)

Alternatives	E1 (kWh/m^3)	E2 (–)	E3 (kg CO_2eq)	E4 (%)	E5 (%)
OS1-HS	0.27	1.37	161.5	0	100
OS1-LS	0.29	2.06	80.9	0	100
OS2-HS	0.24	1.51	151.0	2.9	51.7
OS2-LS	0.23	1.83	67.5	6.3	47.6
Preference direction	↓	↓	↓	↑	↓
Weights	0.2	0.2	0.3	0.2	0.1

In a rough analysis based only on the number of metrics, it seems that the best option is OS2-LS (i.e., 78% of water is treated at Tavira WTP and 22% in Beliche WTP) and the worst is OS1-LS. To apply SAW method the decision matrix needs to be normalized. If the metric preference direction is of minimization Eq. (16) should be used otherwise Eq. (17) is used.

$$e_{ij} = \frac{\max e_{ij}}{e_{ij}} \tag{16}$$

$$e_{ij} = \frac{e_{ij}}{\max e_{ij}} \tag{17}$$

The normalized decision matrix obtained is shown in Table 3.

Table 3. Normalized decision matrix

Alternatives	E1	E2	E3	E4	E5
OS1-HS	1.07	1.5	1.0	0.0	1.0
OS1-LS	1.00	1.0	2.0	0.0	1.0
OS2-HS	1.21	1.4	1.1	0.5	1.9
OS2-LS	1.26	1.1	2.2	1.0	2.1
Weights	0.2	0.2	0.3	0.2	0.1

The results obtained using SAW method to rank the different alternatives, considering the normalized decision matrix in Table 3, are presented in Fig. 4.

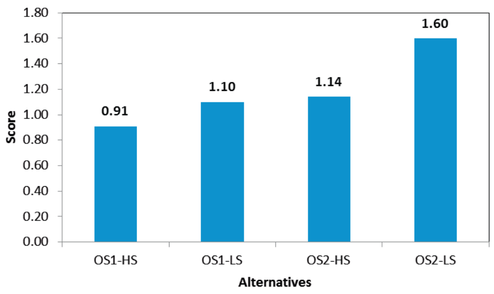

Fig. 4. Ranking obtained with SAW method.

The Decision Deck platform was used to apply the ELECTRE III method and the results obtained are in Fig. 5.

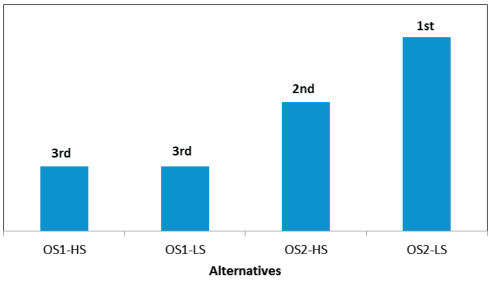

Fig. 5. Ranking with ELECTRE III method

In both methods, the best option is OS2-LS followed by OS2-HS which means that is better to have Beliche's WTP working the whole year and not only at the high season. The main difference in the results obtained with both methods is that with ELECTRE III the alternatives OS1-HS and OS1-LS are ranked *ex aequo* and that does not happen with SAW method. The results are coherent since OS2-LS is better than all others options in at least four metrics (E1, E3, E4 and E5) and OS2-HS is the second better in other four metrics (E1, E2, E4 and E5).

The main drawbacks of SAW method are that: adding or removing alternatives may change ranking; it is difficult to use for qualitative scales and depends hardly on normalization used. The main advantage is that its simplicity allows using a normal spreadsheet to rank the alternatives.

ELECTRE III is more sophisticated than SAW method, which can use discrimination thresholds incorporating in that way the imperfect nature of the evaluations. If, by one hand, this is an advantage, by the other hand, this can be a drawback because assigning values to these discrimination thresholds is not a trivial task.

7. Conclusions

In this paper the application of two MADM methods to select the best energy efficient option for a water supply service was presented. The two methods used were SAW and ELECTRE III. They were applied to Beliche's system of the MMWWS for the Algarve region in Portugal. The aim of the study was the comparison of the energy efficiency of the system for the two operating schemes and for different demands.

Different energy efficiency metrics were calculated from an energy balance, namely: E1 – Energy in excess per unit of the revenue water; E2 – Ratio of the available energy in excess; E3 – GHG produced from energy use; E4 – Energy production profits; and E5 – Consequence of a failure in Tavira's WTP.

The applications of the two methods have shown that the option is OS2-LS followed by OS2-HS which means that is better to have Beliche's WTP working the whole year and not only at the high season. The main difference between the two methods lies with the last two options since ELECTRE III gives an *ex aequo* rank and SAW does not allow this. Despite this difference the methods gives coherent results.

The main purpose of this work was to compare two methods and see if the results were much different. Most of the existing literature about MCDA presents lots of methods but none of them explains which method is better for one type of cases than other. It is referred that the application of different methods with the same data can give different results but none explains the reasons for it. The problem of selection of an appropriate method for some type of problems is still an open research issue (Guitouni and Martel, 1998).

Before the selection of the method, the problem should be carefully described and structured because it can restrict the application of MCDA methods if a problem is not well-structured. Therefore, structuring the decision problem is one of the most importance stages in the analysis and resolution of a multi-criteria decision problem.

As future work, more metrics should be considered and assessed in the analysis, such as the cost of operation and maintenance of the WTP's. This metric was not included because data were not available. As consequence the problem will be reformulated and perhaps final results may change.

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