A MULTI-CRITERIA APPROACH FOR THE SELECTION OF WASTEWATER TREATMENT SYSTEMS

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ABSTRACT

The inefficiency of Wastewater Treatment Systems (WTS) might be a source of hydrological and environmental pollution, and it also causes problems to public health. The advances of technology have contributed to the development of a diversity of new WTS, but it generates a gap for decision-making regards to the correct use of these treatment systems, with a high number of available alternatives, not easily measurable and often presenting conflicting criteria. In this context, this work presents a literature review aiming to identify relevant economic, social, technical and environmental criteria, which can be used in the selection of WTS. Thus, 48 criteria were identified, as well and their importance was ranked according to a group of academics. Furthermore, an illustrative application was conducted considering 20 available WTS and 12 criteria. The ELECTRE II method was used to rank and allocate the most suitable WTS. This research contributes with a multi-criteria model for the evaluation of WTS and to show its relevance in a real world situation.

INTRODUCTION

The wastewater treatment plants need to be correctly projected to reduce environmental pollution and problems to the population. Despite the existence of several technologies to construct and integrate Wastewater Treatment Systems (WTS), there is still a gap for decision-making process regarding the choice for correct criteria and the procedures to select the best combination of technologies and treatment systems. Given the large number of alternatives, this problem presents a high complexity even more if various criteria are to be considered at the same time. Thus, the identification of the main criteria in terms of economic, social, technical and environmental dimensions, regarding the selection of WTS, is a very relevant issue for both academic and practitioners.
The evolution of the technology has contributed to the diversity of available WTS, so the determination of the ideal combination of WTS has become a complex task (Garrido-Baserba et al., 2012; Tan et al., 2014; Molinos-Senante et al., 2015). To select the most appropriate treatment systems, it is important to consider a large number of intrinsic variables (Molinos-Senante et al., 2015; Zeng et al., 2007; Hakanen et al., 2011; Maurer et al., 2012). Despite this complexity, many countries have performed this selection in a meticulous manner using linear programming models, dynamic programming models, nonlinear programming models and hierarchy grey relational analysis. In fact, inappropriate decisions could generate a high impact in terms of treatment efficiency and costs, which can result in economic pressures as well as negative environmental and social impacts (Kalbar et al., 2012). The environment, social and economic dimensions are the three main elements to be considered to guarantee sustainability in this selection process (Molinos-Senante et al., 2014). Indeed, the efficient and adequate WTS specification has a fundamental role in ensuring the sustainability (Garrido-Baserba et al. 2012; Ashley et al., 2008). The WTS assessment has gained interest in recent years, by the use of integrated models and methods to support decision-making, involving social, environmental and economic criteria correlated with technical aspects as fundamental aspects of the evaluation of potential alternatives. In this way, the goal is to find the relevant criteria, the compromises and trade-offs.

METHODS

A previous literature review was used to identify criteria and their relevance in the WTS selection process. The research method was based on the ProKnow-C (Knowledge Development Process – Constructivist) which consists in a structured process for knowledge generation, following a constructivist view and requiring a constant interaction between the researcher and the research object (Lacerda et al., 2014). It consists in 5 steps: 1) Keywords ("criteria", "selection of wastewater treatment systems", "multi-criteria methods") and databases definition ("Scopus", "ISI" and "Science Direct"); 2) Filters for duplicated works, period ("2015 to 2017") and impact factor delimitation; 3) Titles scanning; 4) Abstracts analysis and 5) Full paper reading. Also, an application considering 20 available WTS and 12 criteria was performed to allocate properly the criteria found in a specific scenario and to illustrate the use of the ELECTRE II method for ranking the suitable WTS.

ELECTRE II method

In the ELELCTRE II method, a weight (*W*) is assigned to each criterion, which grows with the importance of the criterion, and for each ordered pair (*x*,*y*) of alternatives. In this method, concordance and discordance indices are associated with the construction of an outranking relationship.

$$C_{(x,y)} = \frac{\sum W^{>} + W^{=}}{\sum W^{>} + W^{=} + W^{<}} \qquad (1)$$

$W^{>}$ = criteria weights when $x \succ y$, (*x* is preferred to *y*);
$W^{=}$ = criteria weights when $x = y$, (*x* is indifferent to *y*);
$W^{<}$ = criteria weights when $x \prec y$, (*x* is not preferred to *y*);

$$D_{(x,y)} = \max\left[\frac{Z_{yg} - Z_{xg}}{Z_g^{*} - Z_g^{-}}\right] \text{For all } g\text{, where } y \succ x \qquad (2)$$

$(y \succ x)$ = set in which alternative *y* is preferred to alternative *x*;
g = criteria in which $y \succ x$;
Z_{yg} = evaluation of alternative *y* in the criterion *g*;
Z_{xg} = evaluation of alternative *x* in the criterion *g*;
Z_g^{*} = better evaluation for criterion *g*;
Z_g^{-} = worse evaluation for criterion *g*.

The ELECTRE II method exploits two levels of outranking: one strong (S^S) and one weak (S^W) and uses some parameters (p *, q *, p^0, q^0) that serve as boundaries of concordance and discordance, required to identify the relationships of dominance. It provides one complete ordering of alternatives by two complete pre-orders, one descendant from the best alternatives to the worst (RankS), and another from the least favourable alternatives towards the best ones (RankW). The alternatives are analysed in relation to the average of (RankS) and (RankW).

RESULTS

The most cited criteria for the economic perspective are the required land area, net life-cycle cost, investment cost, operation and maintenance, and manpower requirement. In relation to social aspects the criteria: public acceptance, participation and odours were the most highlighted. Technical aspects related to complexity and reliability were the most cited. For the environmental perspective, the most relevant criteria were global warming, sustainable behaviour, phosphorus removal, potential for recover products, and demonstrating heterogeneity of indicators. There may be variations in the criteria classification, depending on the evaluator's point of view. Nevertheless, regarding the prioritization of each criterion when compared to the other, no significant differences were detected. Only criteria related to carbon footprint, local adaptation and avoided costs and revenues, presented a lower relevance if compared to the others. The results shown in Table 1 reveal a coherent set of criteria that consider all aspects involved in this research related to the selection of WTS.

Table 1: Identified Criteria from the Literature

Criteria	**Avg	*Oc	Avg x Oc	Weight	Dimension
Investment cost	12.4%	5	61.8%	6.1%	Economic
Operating and maintenance	12.4%	5	61.8%	6.1%	
Net life cycle cost (ANPV cost)	11.4%	7	79.7%	7.9%	
Revenue and avoided cost	18.8%	1	18.8%	1.9%	
Land area required	13.6%	8	109.0%	10.8%	
Cost per household	13.6%	1	13.6%	1.3%	
Manpower requirement	7.5%	5	37.7%	3.7%	
Sludge disposal cost	5.6%	1	5.6%	0.6%	38%
Applicability	2.0%	1	2.0%	0.2%	Technical
Resilience to hydraulic shocks	9.3%	2	18.5%	1.8%	
Resistance to organic loading shocks	1.8%	1	1.8%	0.2%	
Reliability	5.2%	8	41.8%	4.2%	
Durability	7.5%	5	37.7%	3.7%	
Maturity of technology	8.6%	1	8.6%	0.9%	
Replicability	6.3%	5	31.3%	3.1%	
Coordination with local climate	1.7%	1	1.7%	0.2%	
Coordination with local facilities	1.7%	1	1.7%	0.2%	
Flexibility	6.5%	6	38.8%	3.9%	
Stability of operation	6.4%	1	6.4%	0.6%	
Complexity	3.7%	4	14.9%	1.5%	
Professional skills required for O&P	10.5%	1	10.5%	1.0%	
Technical	24.0%	1	24.0%	2.4%	24%
Organic matter and suspended solids removal	9.8%	1	9.8%	1.0%	Environmental
Organic matter efficiency removal	3.1%	3	9.3%	0.9%	
Suspended solids efficiency removal	1.3%	2	2.7%	0.3%	
Nitrogen and phosphorus efficiency removal	5.9%	2	11.8%	1.2%	
Nitrogen efficiency removal	1.1%	2	2.3%	0.2%	
Phosphorus efficiency removal	2.6%	3	7.9%	0.8%	
Sludge disposal effect	4.9%	1	4.9%	0.5%	
Sewage sludge production	6.1%	3	18.3%	1.8%	
Risk	10.6%	1	10.6%	1.0%	
Renewable energy	12.5%	1	12.5%	1.2%	
Energy consumption	4.4%	2	8.7%	0.9%	
Reaching to treatment degree requirement	15.7%	1	15.7%	1.6%	
Carbon footprint	31.3%	1	31.3%	3.1%	
Environmental impact	13.6%	1	13.6%	1.4%	
Eutrophication	10.1%	5	50.6%	5.0%	
Potential for recover products	2.2%	3	6.7%	0.7%	
Global warming	4.0%	6	23.9%	2.4%	
Promotion of sustainable behavior	3.8%	5	18.9%	1.9%	
Potential dor water reuse	3.7%	2	7.5%	0.7%	
Environmental	10.0%	1	10.0%	1.0%	27%
Local adaptation	18.4%	1	18.4%	1.8%	Social
Odours	7.9%	3	23.6%	2.3%	
Noise	4.9%	2	9.7%	1.0%	
Visual Impact	3.2%	2	6.5%	0.6%	
Public acceptance	3.8%	7	26.4%	2.6%	
Participation	3.8%	5	18.9%	1.9%	10%
Sum		137		100%	100%

*Oc = Number of citations in the literature

**Avg = Average of the weights suggested in the literature

APPLICATION

In order to illustrate how the criteria could be used, an illustrative application was performed as it is presented in Table 3. It is based on a specific wastewater treatment plant of a Brazilian basic sanitation company. The internal procedures of the company were considered, as well as, the evaluation scales for each criterion and alternative. In order to use the ELECTRE II method, a normalization procedure was applied as presented in Table 2. This normalization was necessary to organise the criteria in order of preference, e.g., the criterion “Investment Cost” is better if it is lower, and on the other hand the criterion “Reliability” is better if it is higher.

Table 2: Scales and Normalization of the Selected Criteria

Criteria	Description	Measuring Scale	Normalization
Land area required	Ideal minimum space required considering the system capacity per number of inhabitants.	(m^2/inhab)	Midpoint
Reliability	Estimation of the probability of future failures which impact in the treatment efficiency and quality.	+ LowLow ++ Low +++ Acceptable ++++ High	1 2 3 4
Complexity	Related to the level of required qualification for maintenance.	+++++ HighHigh	5
Investment cost	Costs related to the installation of the system per number of inhabitants.	($/inhab)	Midpoint
Operation and Maintenance	Costs related to the installation of the system per number of inhabitants per year.	($/inhab/year)	Midpoint
ANPV cost	Annualised Net Present Value.	$ (Dollar)	$ (Millions)
Global warming	Potential to cause impact on the environment	0 to 10	points
Replicability	Replicability of the system in different scenarios.	+ ++ ++ +++ ++++ +++++ LowLow Low Acceptable High HighHigh	1 2 3 4 5
Removal of organic matter DQO (%)	Efficiency to removal organic matter DQO.	0 to 100%	100% = High Efficiency
Manpower	Manpower needs.	1 to 5	5 = high
Sludge Production	Production of sludge per year	(Kg/inhab/year)	Midpoint
Public acceptance	Degree of acceptance by the population	5 to 15	15 = great acceptability

Table 3 presents twenty possible WTS which were classified according to the 12 criteria presented in Table 2. As indicated in Table 4, slow infiltration, UASB reactor + anaerobic filter and quick infiltration, are ranked in the first, second and third positions, respectively. Therefore, the slow infiltration is the optimal alternative for the studied wastewater treatment plant. This outcome is reasonable considering the low cost of this system, once the high representativeness of the economic dimension, as well as the environmental aspects of this system. The UASB reactor followed by anaerobic filter is more mechanized and have smaller land requirements than other alternatives at the same time it provides a good effluent quality, however it is more expensive than the first ranked system. The farthest ideal solution was the integrated pond systems (a9).

Table 3: Twenty Alternative Wastewater Treatment Systems

Alternatives	Required land area (m^2/inhab)	Reliability	Complexity	Investiment cost ($/inhab)	Operation/Maintenance ($/inhab/year)	ANPV cost ($ - dollar)	Global warming	Replicability	Removal of organic matter DQO (%)	Manpower ($/inhab./year)	Sludge Production (Kg/inhab./year)	Public acceptance
Weigths from literature review	10.8%	4.2%	1.5%	6.1%	6.1%	7.9%	2.4%	3.1%	1.0%	3.7%	1.8%	2.6%
Normalized Weights for this application	**21.1%**	**8.2%**	**2.9%**	**11.9%**	**11.9%**	**15.4%**	**4.7%**	**6.1%**	**2.0%**	**7.2%**	**3.5%**	**5.1%**
a1 – Advanced primary treatment (A)	0.04-0.06	++++	+++	40-60	7.5-15	$73,700,424	2	+++	65	3	730-2500	14
a2 – Reactor UASB + Complete aerated ponds + decanter	0.10-0.30	+++	+++	40-90	5.0-9.0	$72,715,934	5	+++	72.5	3	150-300	5
a3 – Reactor UASB + facultative aerated ponds	0.15-0.30	++++	++++	40-90	5.0-9.0	$69,743,666	5	++++	72.5	4	150-300	7
a4 – Reactor UASB + Biological filter High-pressure perch	0.10-0.20	++++	+++	60-90	5.0-7.5	$67,210,998	3	+++	80.5	3	180-400	13
a5 – Septic tank + infiltration	1.00-1.50	+++	++++	60-100	3.0-5.0	$61,394,655	2	++++	90	5	110-360	15
a6 – Reactor UASB + Superficial runoff	1.50-3.00	++++	+++++	50-90	5.0-7.0	$60,592,391	3	+++++	77.5	5	70-220	15
a7 – Anaerobic pond + facultative pond + high rate pond	2.00-3.50	++++	+++	50-90	3.5-6.0	$60,414,059	4	+++	76.5	3	55-160	9
a8 – Anaerobic pond + facultative pond + algae removal	1.70-3.20	++++	+++	50-90	3.5-6.0	$58,618,628	3	+++	79	3	60-90	15
a9 – Anaerobic pond + facultative pond + maturation pond	3.00-5.00	+++	+++	50-100	2.5-5.0	$57,665,862	4	+++	76.5	3	55-160	15
a10 – Reactor UASB + Polishing ponds	1.50-2.50	++++	+++++	40-70	4.5-7.0	$56,748,639	3	+++++	76.5	3	150-250	15
a11 – Primary treatment (septic tanks)	0.03-0.05	++++	+++	30-50	1.5-2.5	$52,958,618	2	+++	30	3	110-360	15
a12 – Reactor UASB + Anaerobic filter	0.05-0.15	++++	+++	45-70	3.5-5.5	$50,397,046	4	+++	75	3	150-300	15
a13 – Wetlands	3.00-5.00	++++	+++++	50-80	2.5-4.0	$49,997,518	0	+++++	80	5	0	14
a14 – Superficial runoff	2.00-3.50	++++	+++++	40-80	2.0-4.0	$46,115,446	1	+++++	80	5	0	15
a15 – Facultative pond	2.00-4.00	++++	+++++	40-80	2.0-4.0	$41,827,667	2	+++++	72.5	5	35-90	15
a16 – Anaerobic pond + facultative pond	1.20-3.00	++++	+++++	30-75	2.0-4.0	$41,793,179	3	+++++	72.5	5	55-160	13
a17 – Quick Infiltration	1.00-5.00	++++	++++	30-70	1.5-3.5	$38,475,841	1	++++	86.5	4	0	14
a18 – Reactor UASB	0.03-10.0	+++	++++	30-50	2.5-3.5	$34,552,935	3	++++	62.5	4	70-220	15
a19 – Slow infiltration	10.0-50.0	++++	++++	20-60	1.0-3.0	$31,822,970	1	++++	90	4	0	15
a20 – Conventional primary treatment	0.02-0.04	++++	+++	30-50	1.5-2.5	$27,809,621	2	+++	30	3	330-730	14

Table 4: Generated Ranking by ELECTRE II

RankW	RankS	Average	Alternative	**Ranking**
1.0	1.0	1.0	a19	**1st**
2.0	1.0	1.5	a12	**2 nd**
2.0	2.0	2.0	a17	**3 rd**
2.0	2.0	2.0	a18	**4 th**
3.0	3.0	3.0	a10	**5 th**
3.0	3.0	3.0	a16	**6 th**
6.0	1.0	3.5	a20	**7 th**
7.0	1.0	4.0	a1	**8 th**
4.0	4.0	4.0	a8	**9 th**
4.0	4.0	4.0	a14	**10 th**
7.0	2.0	4.5	a11	**11 th**
5.0	5.0	5.0	a4	**12 th**
5.0	5.0	5.0	a15	**13 th**
6.0	5.0	5.5	a7	**14 th**
6.0	6.0	6.0	a3	**16 th**
6.0	6.0	6.0	a13	**16 th**
7.0	6.0	6.5	a5	**17 th**
7.0	7.0	7.0	a2	**18 th**
7.0	7.0	7.0	a6	**19 th**
7.0	7.0	7.0	a9	**20 th**

CONCLUSIONS AND FURTHER RESEARCH

Considering the existence of a large number of criteria, this paper highlights the importance of using multi-criteria tools for decision-making in the sanitation context, since choosing a system based on a few criteria or inadequate criteria can have serious long-term consequences. For an overall analysis, it is necessary to consider environmental, social, economic and technological aspects. In this way, this study has contributed to increasing the knowledge about which relevant criteria can be used in the selection of Wastewater Treatment Systems. An example was used to illustrate the use of a multi-criteria model to operationalize the selection process. The approach proposed here can be applied to other situations in a way to avoid subjectivity and randomness.

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