Selection of a Sustainable Municipal Wastewater Treatment Technology: A Multi-Criteria Decision Analysis Approach Using AHP and TOPSIS with Fuzzy Sets

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Abstract

This paper presents the use of two Multi-Criteria Decision Analysis (MCDA) tools with Fuzzy Set Theories, namely Fuzzy Analytical Hierarchical Process (FAHP) and Fuzzy Technique for Order Preference by Similarity to the Ideal Solution (FTOPSIS), for aiding experts on the selection of the most sustainable wastewater treatment technology (WWT). 8 experts with different roles on the selection of WWT was invited to provide inputs. The selection process integrated sustainability by considering 4 major criteria Economical, Environmental, Social and Technical each then having its own sub-criteria.

Keywords
Multi-Criteria Decision Analysis, Fuzz Analytical Hierarchical Process, Wastewater Treatment Technology

1. Introduction

Globally, around 29% of the population lacks access to safe drinking water (United Nations, 2018). A report from Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) indicated a water shortage last year caused by El Niño which started in the last quarter of 2018 and continued until August of the same year (PAGASA, 2019). In 2011, a study conducted by the University of the Philippines reported that the water supply deficit in Metro Manila would occur as early as 2017 if there were no new water sources to be developed (NEDA, 2015). In the year 2014, the global water stress level recorded is 13%. The regions in Eastern and South-Eastern Asia recorded a water stress level of 19% making them 3rd in the world which experiences high water stress levels. Water stress is defined as the ratio of the withdrawn freshwater from the total renewable freshwater resource (United Nations, 2018). These reports provided insights that if the current withdrawal of freshwater will continue a future water scarcity is likely to happen.

One of the many ways to address the issue of water scarcity and water stress is to use non-conventional waters such as desalinized water, drainage water, and reused wastewater as new sources (Garcia & Pargament, 2015; Sadr et al., 2018; United Nations, 2018). Selection of an appropriate WWT technology is a vital and complex process (Castillo et al., 2017; Mahjouri et al., 2017; Bozkurt et al., 2016; Dursun, 2015). Choosing the wrong technology will impact cost, efficiency, and water quality (Kalbar et al., 2012).

In the selection of their WWT technology, both concessionaires conduct a multi-criteria decision analysis (MCDA) which is detailed below. MCDA is a tool that was developed to aid decision-makers (DM) in selecting the best alternative or solution to a goal while considering multiple and conflicting objectives or criteria (Ishizaka & Nemery, 2013; Triantaphyllou, 2000). It is widely used in areas such as water resources management: infrastructure selection; water allocation; water policy and the planning of supply; water quality management (Zardari et al., 2015). In all these reports, the alternatives with the highest scores were selected.
However, none of the recent reports mentioned the use of any specific MCDA tool. This was evident as weight criteria were simply assigned and scores were tallied by simply multiplying it to the assigned weights. Weight criteria are crucial values in a selection process as it greatly affects the result. Simply assigning its values is prone to certain biases that are present from all stakeholders’ inputs, thus leading to poor analysis (Montibeller & Von Winterfeldt, 2015). Also, manipulation of the results is very easy in the absence of an MCDA tool.

The aforementioned approaches used in the MCDA were not holistic and traditional as it only considered technical and economical (Popovic et al., 2013) with the latter being the key driver (Bozkurt et al., 2016). It is important to note that WWT technology selection’s goal should be to ensure sustainability. Thus, other factors should be considered (Chhipi-Shrestha et al., 2017). Recent works of the literature show that selection of the most sustainable WWT accounts for 4 major factors namely; Economical, Environmental, Social, and Technical factors (Mahjouri et al., 2017; Ren & Liang, 2017; Zyoud et al., 2016).

In this light, it will be of interest to revisit the selection process of WWT technology by Philippine water concessionaires to pursue holistic optimization, not just based on cost but also in consideration of sustainability concerns. Consequently, an answer must be sought to the research question, what would be a better and more holistic MCDA approach that can be adopted as a decision model in the selection of a WWT technology?

As such, the study aimed to achieve the following objectives: (1) to assess the current MWT technology selection processes and review the criteria used in decision making by Philippine water concessionaires; (2) to determine the gaps between the current practice and the best approach in solving multi-criteria decision problems involving sustainability - social, economic and environmental factors; and (3) to develop a decision-support tool (DST) to assist the Philippine water concessionaires in selecting the best WWT technology with a sustainability-driven approach for optimal holistic benefits.

The study focused on the development of a sustainability-based DST for selecting a feasible municipal WWT technology given different scenarios and conditions. Its unit of analysis would be the Philippine concessionaires and the data gathered came from reports that are not publicly available and are mostly proprietary and considered confidential. With these data protected under the “Data Privacy Act of 2012”, this study could not disclose the specific source of sensitive information but data and information were objectively transcribed without changing the context and values of such.

2. Methodology

In order to select the most sustainable WWT technology, the study will be guided by the conceptual framework shown in Figure 2.1.

![Figure 2.1. Conceptual Framework for Selection of a Sustainable Wastewater Treatment Technology](image)

2.1 Assessment of the Current Practice
The area of study will be based on the actual technology selection of a municipal wastewater treatment plant which is to be located in Manila, Philippines. The WWT facility is about to cater to an average flow of 65 million liters per day (MLD) of wastewater coming from several pumping stations and interceptors. For each given alternative, all equipment will be the same except for the biological treatment stage. It is important to note that the feasibility study for the selection of the technology for the said municipal WWT is already done. Thus, a detailed assessment of how the selection process was conducted is necessary. This stage aims to understand how and determine what the gaps in the selection process are.

### 2.2 Identification of Major and Sub-Criteria

Major Criteria to be used are the 4 sustainability factors; economic, environmental, social, and technical (Mahjouri et al., 2017; Ren & Liang, 2017; Zyou et al., 2016). The same major criteria are considered for other fields such as solid waste and renewable energy (Govind Kharat et al., 2019; Mardani et al., 2017; Ozorhon, Batmaz, & Caglayan, 2018). Table 2.2.1 represents the derived sub-criteria from the related literatures and adapts some of the current criteria considered by the concessionaires.

<table>
<thead>
<tr>
<th>MAJOR CRITERION</th>
<th>SUB-CRITERION</th>
<th>DEFINITION</th>
<th>REFERENCES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economical</td>
<td>Capital Expenditures</td>
<td>Cost required to implement an alternative.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Operational and Maintenance Expenditures</td>
<td>Cost associated in keeping and controlling an alternative.</td>
<td></td>
</tr>
<tr>
<td>Environmental</td>
<td>Energy Consumption</td>
<td>Annual energy consumption from blowers.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Land Requirement</td>
<td>Total amount of land required.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sludge Production</td>
<td>Total amount of sludge produced upon treatment of wastewater.</td>
<td>(Mahjouri et al., 2017)</td>
</tr>
<tr>
<td>Social</td>
<td>Public Acceptance</td>
<td>General public acceptance (noise, odor and visual impact) especially of residents living nearby.</td>
<td></td>
</tr>
</tbody>
</table>
2.3 Fuzzy AHP (FAHP)

AHP model was proven to be useful in water resource management which includes WWT selection and other applications (Kubler et al., 2016; Mardani et al., 2017). In 2007, a study reviewed 113 publish paper related to water resource management. The result showed that AHP is one of the most applied tools (Hajkowicz & Collins, 2007).

First developed by Van Laarhoven & Pedrycz, 1983. It was an extension of Thomas L. Saaty's work. It was a combination of fuzzy logic and AHP. Then Buckley (1985) criticized Van Laarhoven and Perdrcz's FAHP method. He then also developed a FAHP. FAHP Procedure are as follows:

1. Structure a decision hierarchy as shown in figure 2. Figure 2 shows a 3 layered FAHP. The 1st layer describes the main goal of the FAHP which is to select the most sustainable WWT technology. 2nd layer identifies the major criteria while the 3rd criteria for the sub-criteria. The diagram will also be the guide for formulating the questionnaire to be answered by the respondents.

2. Construct a traditional pairwise comparison matrix (A) using eq. 1. DMs are to compare the relevance between \(a_{ij}\) the criteria (n, number of criteria) using the fundamental scales in Table 2.3.1 by Saaty, 1990.

\[
A = (a_{ij})_{n \times n} = \begin{bmatrix}
a_{11} & a_{12} & \cdots & a_{1n} \\
a_{21} & a_{22} & \cdots & a_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
a_{n1} & a_{n2} & \cdots & a_{nn}
\end{bmatrix}
\] (1)

3. Construct a fuzzy pairwise comparison matrix (\(\tilde{A}\)) using eq. 2. and translate these scales to triangular fuzzy numbers (TFN) shown in Table 2.3.1. The \(\Delta\) denotes a fuzzification factor which is equivalent to 1 (Tesfamariam & Sadiq, 2006).
\[
\tilde{A} = (\tilde{a}_{ij})_{n \times n} = \begin{bmatrix}
\tilde{a}_{11} & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\
\tilde{a}_{21} & \tilde{a}_{22} & \cdots & \tilde{a}_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
\tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & \tilde{a}_{nn}
\end{bmatrix}
\] (2)

4. Aggregate the DM’s fuzzy ratings using eq. 3.

\[
\tilde{a}_{ij} = \frac{1}{K} \left[ \tilde{a}_{ij}^1 + \tilde{a}_{ij}^2 + \cdots + \tilde{a}_{ij}^K \right]
\] (3)

5. Calculate the fuzzy geometric mean values using eq. 4.

\[
\tilde{r}_i = (\tilde{a}_{i1} \otimes \tilde{a}_{i2} \otimes \cdots \otimes \tilde{a}_{in})^{1/n}
\] (4)

6. Calculate the fuzzy weights using eq. 5.

\[
\tilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \tilde{r}_2 \oplus \cdots \oplus \tilde{r}_n)^{-1}
\] (5)

7. Defuzzification using center of area method by using eq. 6.

\[
w_d = \frac{\tilde{w}_i + \tilde{w}_m + \tilde{w}_u}{3}
\] (6)

8. Determine the normalized weights using eq. 7.

\[
w_N = \frac{w_d}{\sum_{i=1}^{n} w_{di}}
\] (7)

Table 2.3.1 Fundamental Scales with its equivalent Triangular Fuzzy Scale (Saaty, 1990; Tesfamariam & Sadiq, 2006)

<table>
<thead>
<tr>
<th>Intensity of Importance on an absolute scale</th>
<th>Triangular Fuzzy Number (TFN)</th>
<th>Definition</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(1,1,1)</td>
<td>Equal Importance</td>
<td>Two activities contribute equally to the objective</td>
</tr>
<tr>
<td>3</td>
<td>(3 - Δ, 3, 3 + Δ)</td>
<td>Moderate importance of one over the other</td>
<td>Experience and judgement strongly favor one activity over another</td>
</tr>
<tr>
<td>5</td>
<td>(5 - Δ, 5, 5 + Δ)</td>
<td>Essential or strong importance</td>
<td>Experience and judgement strongly favor one activity over another</td>
</tr>
</tbody>
</table>
Very strong importance
An activity is strongly favored, and its dominance demonstrated in practice

Extreme importance
The evidence favoring one activity over another is of the highest possible order of affirmation

Intermediate values between the two adjacent judgments
When compromise is needed

If activity \( i \) has one of the above numbers assigned to it when compared with activity \( j \), then \( j \) has the reciprocal value when compared with \( i \)

2.4 Fuzzy TOPSIS (FTOPSIS)

TOPSIS originally developed by Hwang & Yoon (1981) was a tool based on the concept that the chosen alternative should have the shortest and farthest distance from the positive ideal and negative ideal solution. It was then further developed by incorporating fuzzy set theories (Chen, 2000). FTOPSIS procedure are as follows:

1. Construct a pairwise comparison matrix using eq. 8. DMs are to compare the relevance between the options using the linguistic variables in table 2.4.1 proposed by Chen (2000).

\[
D = (x_{ij})_{m \times n} = \begin{bmatrix}
    x_{11} & x_{12} & \cdots & x_{1n} \\
    x_{21} & x_{22} & \cdots & x_{2n} \\
    \vdots & \vdots & \ddots & \vdots \\
    x_{m1} & x_{m2} & \cdots & x_{mn}
\end{bmatrix}
\]  

(8)

2. Similar with FAHP, using eq. 9 construct a fuzzy pairwise comparison matrix by translating these linguistic variables to triangular fuzzy members shown in table 2.3.1.

\[
\bar{D} = (\bar{x}_{ij})_{m \times n} = \begin{bmatrix}
    \bar{x}_{11} & \bar{x}_{12} & \cdots & \bar{x}_{1n} \\
    \bar{x}_{21} & \bar{x}_{22} & \cdots & \bar{x}_{2n} \\
    \vdots & \vdots & \ddots & \vdots \\
    \bar{x}_{m1} & \bar{x}_{m2} & \cdots & \bar{x}_{mn}
\end{bmatrix}
\]  

(9)

Table 2.3.1 Linguistic Variables with equivalent TFN (Chen, 2000)
3. Aggregate the DM’s fuzzy ratings using eq. 10.

\[
\bar{x}_{ij} = \frac{1}{K} \left[ \bar{x}_{ij}^1 + \bar{x}_{ij}^2 + \cdots + \bar{x}_{ij}^K \right]
\]  

(10)

4. Determine the benefit (B) and cost (C) criteria respectively then construct the normalize fuzzy decision matrix. Use eq. 11 if its benefit criteria and use eq. 12 if its cost criteria.

\[
\bar{r}_{ij} = \left( \frac{a_{ij}}{c_{ij}}, \frac{b_{ij}}{c_{ij}}, \frac{c_{ij}}{c_{ij}} \right), j \in B, c_j^+ = \max c_{ij}
\]

(11)

\[
\bar{r}_{ij} = \left( \frac{a_{ij}^-}{c_{ij}}, \frac{a_{ij}^-}{b_{ij}}, \frac{a_{ij}^-}{a_{ij}} \right), j \in C, a_{ij}^- = \min a_{ij}
\]

(12)

5. Using the weights calculated in the FAHP, construct the weighted normalize fuzzy decision matrix. Use eq. 13.

\[
\tilde{v}_{ij} = \bar{r}_{ij}(\cdot)w_N
\]

(13)

6. Determine the fuzzy positive-ideal solution (FPIS, \(A^*\)) and fuzzy negative-ideal solution (FNIS, \(A^-\)) using eq. 14.

\[
A^* = (\tilde{v}_{1}^*, \tilde{v}_{2}^*, \cdots, \tilde{v}_{n}^*)
\]

\[
A^- = (\tilde{v}_{1}^-, \tilde{v}_{2}^-, \cdots, \tilde{v}_{n}^-)
\]

(14)

7. Calculate the distance between FPIS and FNIS of each alternative using eq. 15 and eq. 16 respectively.

\[
d_i^* = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_{j}^*)
\]

\[
= \sqrt{\frac{(\tilde{v}_{1ij} - \tilde{v}_{j}^*)^2 + (\tilde{v}_{2ij} - \tilde{v}_{j}^*)^2 + (\tilde{v}_{3ij} - \tilde{v}_{j}^*)^2}{3}}
\]

; \(\tilde{v}_{j}^* = (1,1,1)\)
\[ d_i^- = \sum_{j=1}^{n} d(v_{ij}, \bar{v}_i^-) \]
\[ = \sqrt{\frac{(\bar{v}_{1ij} - \bar{v}_i^-)^2 + (\bar{v}_{2ij} - \bar{v}_i^-)^2 + (\bar{v}_{3ij} - \bar{v}_i^-)^2}{3}} \]
\[ ; \bar{v}_i^- = (0,0,0) \]  

(16)

8. Using eq. 17, calculate the closeness coefficient (CC) of each alternative.

\[ CC_i = \frac{d_i^-}{d_i^- + d_i^+} \]  

(17)

9. Rank the alternatives.

3. Results and Discussion

Workshops were conducted thru MS teams as face-to-face meetings are not allowed due to the pandemic. It was divided into 2 parts; first was the introduction of MCDA basics and FAHP and secondly the FTOPSIS. 8 experts (Saaty & Özdemir, 2014) with different roles for WWT procurement, design and construction management were invited. Prior to the discussion the questionnaire was emailed. Summary of the decision makers is on Table 3.1. Upon submission of questionnaires, the researcher has used MS Excel to aid the calculation.

Table 3.1 Summary of Decision Makers Details

<table>
<thead>
<tr>
<th>Educational Attainment</th>
<th>Years of Experience</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS Environmental Engineering</td>
<td>5</td>
<td>Environmental Engineer</td>
</tr>
<tr>
<td>BS Civil Engineering</td>
<td>6</td>
<td>Design Manager</td>
</tr>
<tr>
<td>BS Chemical Engineering</td>
<td>8</td>
<td>Process Engineer</td>
</tr>
<tr>
<td>BS Chemical Engineering BS Chemistry</td>
<td>13</td>
<td>Design Manager</td>
</tr>
<tr>
<td>BS Civil Engineering</td>
<td></td>
<td>Project Manager</td>
</tr>
<tr>
<td>BS Environmental and Sanitary Engineering</td>
<td>10</td>
<td>Project and Design Coordinator</td>
</tr>
<tr>
<td>MS Civil and Environmental Engineering</td>
<td>5</td>
<td>Project and Design Coordinator</td>
</tr>
<tr>
<td>BS Civil Engineering</td>
<td>5</td>
<td>Hydraulic Engineer</td>
</tr>
<tr>
<td>BS Chemical Engineering</td>
<td>6</td>
<td>Process Engineer</td>
</tr>
</tbody>
</table>
3.1 Current Practice

A discussion of the details of the selection process was done thru an email inquiry. The researcher directly asked the project manager and process engineer of this project. Based on the discussion conducted, the identified gaps on the selection process were the following: 1.) It is confirmed there was no actual MCDA tool used both for criteria weight and alternative ranking calculation. 2.) Traditional approach was conducted. Major criteria considered were only Economical and Technical. Environmental and Social criteria were considered sub-criteria of the Technical criteria. 3.) Differing views of stakeholders were not captured as assigned scores, both for criteria weight and rank score were simply agreed. 4.) Major and Sub-criteria weights were simply assigned with the 2 major having a 50-50 split. 5.) Ranking scores were simply multiplied to the assigned criteria weight. Ranking scales used have negative values which resulted to some negative value results.

3.2 Integration of Sustainability Criteria

During the 1st part of the workshop, gaps on the current selection process were discussed. It was presented that sustainability should be the key goal on selection of WWT technology. Thus, in the proposed selection process Environmental and Social criteria were added as major criteria with its respective sub-criteria as seen in Table 3.2.1.

Table 3.2.1 Summary of FAHP Results

<table>
<thead>
<tr>
<th>Major</th>
<th>Weight</th>
<th>Sub-Criteria</th>
<th>Weight</th>
<th>Combined Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economical</td>
<td>27.16%</td>
<td>CAPEX</td>
<td>59.20%</td>
<td>16.10%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OPEX</td>
<td>40.71%</td>
<td>11.10%</td>
</tr>
<tr>
<td>Environmental</td>
<td>28.56%</td>
<td>Energy Requirement</td>
<td>39.74%</td>
<td>11.30%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Land Requirement</td>
<td>36.76%</td>
<td>10.50%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sludge Production</td>
<td>23.50%</td>
<td>6.70%</td>
</tr>
<tr>
<td>Social</td>
<td>14.06%</td>
<td>Public Acceptance</td>
<td>69.02%</td>
<td>9.70%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Added Jobs</td>
<td>30.98%</td>
<td>4.40%</td>
</tr>
<tr>
<td>Technical</td>
<td>30.22%</td>
<td>Flexibility</td>
<td>48.76%</td>
<td>14.70%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maturity</td>
<td>22.40%</td>
<td>6.80%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Availability</td>
<td>28.84%</td>
<td>8.70%</td>
</tr>
</tbody>
</table>

3.3 FAHP

Results are summarized in Table 3.2.1. It shows that amongst the experts Technical is the top consideration. Economical ranks 3rd only next to Environmental with a minor difference of 1.40%. The process shows that upon using FAHP "Economical" factor is not the key driver. Major key drivers will either be a combination of "Technical and Environmental", "Technical and Economical" or "Environmental and Economical". This is consistent as upon observing the "Combined Weights", it shows that the top 4 criteria, which has a total of 53.2%, are CAPEX, Flexibility, Energy Requirement, and OPEX.

3.4 FTOPSIS
The sub-criteria identified are divided into 2 groups; quantitative and qualitative. Under quantitative group are CAPEX, OPEX, Energy Requirement, Land Requirement, and Sludge Production which were also identified as the "Cost" criteria. Values were based on the calculated data during the design process. All the qualitative criteria are considered "Benefit-cost" which are: Public Acceptance, Added Jobs, Flexibility, Maturity, and Availability. The calculation shows that Alternative 2 (A2) which has the highest closeness coefficient is the most sustainable technology base on the given set of criteria. See Table 3.4.1 for a summary of FTOPSIS results.

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>FPIS</th>
<th>FNIS</th>
<th>CCi</th>
</tr>
</thead>
<tbody>
<tr>
<td>WWTT1</td>
<td>9.46</td>
<td>0.56</td>
<td>0.056</td>
</tr>
<tr>
<td>WWTT2</td>
<td>9.44</td>
<td>0.58</td>
<td>0.058</td>
</tr>
<tr>
<td>WWTT3</td>
<td>9.53</td>
<td>0.49</td>
<td>0.049</td>
</tr>
</tbody>
</table>

4. Conclusion

This study provided a framework for aiding water concessionaires in selecting a wastewater treatment technology using MCA tools. It started with identifying the gaps in the current selection process thru an assessment. The assessment showed 5 gaps. Notable on these gaps were the absence of any MCDA tool and the traditional approached used as showed with Economical and Technical criteria only being considered as major criteria.

The second objective is to ensure that sustainability will be a key goal. Environmental and Social criteria were added. This resulted in the selection process to be holistic. Finally, the proposed decision support tool was used. FAHP and FTOPSIS were utilized to calculate criteria weights and ranking scores respectively. Workshops thru MS teams were conducted with 8 experts who provided valuable inputs enabling this study to select the most sustainable WWT technology within the given criteria. Results verified that with appropriate tools to be used selection process will not be cost-driven but sustainability-driven.

References


Biographies

**Engr. Nico B. Carlos** is a practicing Mechanical Engineer in the Philippines. He is currently working for a consultancy firm for infrastructure projects, which handles municipal water and wastewater treatment projects. He is taking his Master’s Degree in Engineering Management at the Mapua University of Technology.

**Marvin I. Noroña** is the Managing Partner and Senior Consultant of the Socio-Economic and Empowerment Development Solutions (SEEDS), Inc. and currently a faculty at the Mapua University School of Industrial Engineering & Engineering Management and School of Graduate Studies. He earned his BS Industrial Engineering and MBA degrees from University of the Philippines and is a Doctor in Business Administration candidate finishing his thesis in lean and green manufacturing. His research interests are in the areas of sustainability, supply & operations management, production & service systems improvement, strategic planning and management, lean six sigma, and design thinking.