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Optimal Selection of Aerobic Biological Treatment for a Petroleum Refinery Plant

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Aerobic biological treatment has been known to be an integral part of a typical wastewater treatment plant that reduces the pollution load of wastewater from either municipality or industry having soluble organic contaminants. For example, the conventional activated sludge process has been widely used in a long time but a variety of biological treatment systems were also being considered in recent years to meet a more stringent discharge standards. In designing such wastewater treatment plant, several criteria have to be taken into account that includes the technical, socio-economic and environmental aspects of the decision problem. This work thus applies a multiple criteria analysis based on Group Fuzzy AHP for optimal selection of the different aerobic biological treatment technologies. This technique decomposes the decision problem into a hierarchic structure and derives priority weights for the ranking of the alternatives. The decision model also incorporates the ambiguity-type uncertainty when eliciting pairwise comparison judgment from a domain expert. A case study applied to a petroleum refinery plant is presented considering the following alternatives: 1) conventional activated sludge system (CAS); 2) sequencing batch reactor (SBR); 3) integrated fixed film activated sludge system (IFAS); and 4) membrane bioreactor (MBR). These wastewater treatment systems were then evaluated and compared with respect to the following criteria: 1) economic sub-criteria such as the capital and operating cost; 2) environmental sub-criteria such as the treated effluent quality, ability to adjust to hydraulic and pollutant loading, ability to cope with oil ingress, and land footprint; 3) technical sub-criteria such as pre-treatment and secondary clarifier requirement, reliability and validity of technology, and complexity to operate and control. The Group Fuzzy AHP model showed that SBR is the most preferred option followed by CAS as regard to aerobic biological system for the treatment of petroleum refinery wastewater. Indications suggest from sensitivity analysis that the ranking of the alternatives is influenced largely by the weighting of economic and environmental aspects.

1. Introduction

Energy demand is expected to increase by 60 % over the projection period 2010 - 2040 wherein oil remains the energy type with the largest share (OPEC, 2014). This translates to a global demand for oil of around 111.1 million barrels per day (mb/d) by year 2040 from 90 mb/d of year 2013. This increase in global oil demand will result to an increase in petroleum refinery wastewater (PRWW), a by-product of an oil refinery plant. PRWW contains a complex mixture of its components which are mostly oils, grease and other petroleum based organics (Diya'uddeen et al., 2011). This type of wastewater could cause major environmental pollution if discharged to the environment without prior treatment. Thus, a wastewater treatment plant (WWTP) is necessary to treat PRWW prior to its ultimate disposal to the environment.

IPIECA (2010) reported that the typical WWTP for PRWW includes the following process train: Primary Oil/Water Separation → Secondary Oil/Water Separation → Equalization → Biological Treatment → Clarification → Sand Filtration. These unit processes range from physical to biological processes. The latter (i.e. biological treatment) is considered to be the main treatment unit wherein the use of microorganisms is

necessary to degrade the pollutants present in the PRWW. Moreover, biological treatment processes are considered to be economical for the treatment of PRWW (Ishak et al., 2012).
However, recent advances in research show other advanced biological treatment processes like enhanced photo-degradation, membrane bioreactor, flocculation and ceramic membrane filtration as alternatives in treating PRWW (Yavuz et al., 2010). This raise a problem to decision-makers as to what possible technology (conventional or advanced) they could employ should they decide to expand their operation to accommodate this increase in oil demand.
This paper aims to evaluate both conventional and advanced biological treatment technologies for the treatment of PRWW. Specifically, four biological treatment technology alternatives will be evaluated, namely: Conventional Activated Sludge (CAS) System, Sequencing Batch Reactor (SBR), Integrated Fixed Film Activated Sludge (IFAS) System and Membrane Bioreactor (MBR) (Mittal, 2011). These technology alternatives will be evaluated against a set of criteria to help prioritize options. In doing so, this would require a use of multiple attribute decision making (MADM) techniques to provide a systematic approach to alternatives prioritization.
One of the most widely used MADM techniques is the Analytic Hierarchy Process (AHP) developed originally by Saaty (1977) to derive ratio-scale priorities from a hierarchic structure. Thus far, AHP has proven its effectiveness as a decision analytic model to include and measure all important tangible and intangibles, quantitatively measurable and qualitative factors of a complex decision situation. For example, AHP has been applied in wastewater treatment selection for small cheese factories (Bottero et al., 2011), for domestic wastewater discharges (Tan et al., 2014), among others. In this study, a variant of AHP was developed to address the uncertainty involved in a group decision making environment to be applied in the prioritization of aerobic biological treatment for a petroleum refinery plant in the Philippines.

2. Methodology

The procedure of the Group fuzzy AHP is described as follows:
Step 1. Decompose the decision problem in a linear hierarchical structure (e.g., see Figure 1). For example, the downward arrows in the digraph from Level 1 to Level 2 represent the priority weights of *n* criteria with respect to goal. The downward arrows in the digraph from Level 2 to Level 3 represent the priority weights of *m* alternatives with respect to each criterion.

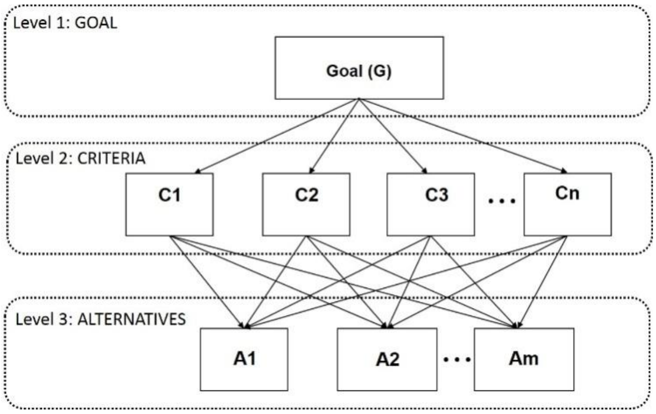

Figure 1: A hierarchical decision structure (Promentilla et al, 2015)

Step 2. Elicit value judgments from stakeholder or expert for pairwise comparison matrices using the 9-point scale representing the intensity of dominance. The dominance can be interpreted in terms of importance, preference, likelihood of one element over the other within the level with respect to an upper level element. For example, the dominance intensity of a '9' in terms of relative importance indicates that one factor is absolutely more important than the other and a '1' indicates indifference or equal importance. The group judgment $\hat{a}_{ij}$ is then represented by a triangular fuzzy number (l_{ij}, m_{ij}, u_{ij}) as shown in Figure 2. The l_{ij} and u_{ij} represent the smallest and the largest rating score obtained from the group, respectively while m_{ij} represents consensus value, i.e., the aggregated individual judgments by geometric mean method. The $\hat{a}_{ij}$ then used as entry to the reciprocal pairwise comparison matrix $\hat{A}$ of order ***n*** (i.e., the number of elements to be prioritized in a cluster) such that:

$$\hat{A}=\begin{bmatrix} \langle 1,1,1\rangle & \hat{a}_{12} & \cdots & \hat{a}_{1n} \\ \hat{a}_{21} & \langle 1,1,1\rangle & \cdots & \hat{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \hat{a}_{n1} & \hat{a}_{n1} & \cdots & \langle 1,1,1\rangle \end{bmatrix} \text{ where } \hat{a}_{ji}=\frac{1}{\hat{a}_{ij}}=\left\langle \frac{1}{u_{ij}},\frac{1}{m_{ij}},\frac{1}{l_{ij}} \right\rangle \tag{1}$$

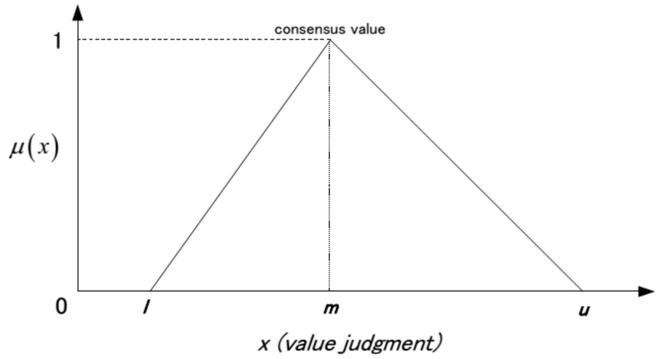

Figure 2: Group fuzzy judgment as represented by triangular fuzzy number (TFN)

The optimal ***w*** is then computed using the proposed nonlinear programming (NLP) formulation (Promentilla et al., 2015):

$$\max \lambda \tag{2a}$$

subject to:

$$a_{ij} - l_{ij} \geq \lambda(m_{ij} - l_{ij}) \quad ; \; a_{ji} - l_{ji} \geq \lambda(m_{ji} - l_{ji}) \tag{2b}$$

$$u_{ij} - a_{ij} \geq \lambda(u_{ij} - m_{ij}) \; ; \; u_{ji} - a_{ji} \geq \lambda(u_{ji} - m_{ji}) \tag{2c}$$

$$\text{where } a_{ij} = {}^{w_i}\!/\!_{w_j} \; ; \; a_{ji} = {}^{w_j}\!/\!_{w_i} \quad \forall \text{ i = 1,..., n-1; j = 2,..., n; j > i} \tag{2d}$$

$$\sum_{k=1}^{n} w_k = 1; \quad w_k > 0 \tag{2e}$$

Note that this method can derive crisp weights even from an incomplete pairwise comparative judgment matrix (PCJM).

Step 3. Compute the crisp priority vector ***w*** from $\hat{A}$ of order ***n*** by approximating the solution ratios ($\boldsymbol{a_{ij}}$) that would maximize $\boldsymbol{\lambda}$, i.e**.,** the highest degree of membership in a membership function o triangular fuzzy numbers indicating the intersection of degree of satisfaction of all computed ratios that would satisfy the initial group fuzzy judgments obtained from at least *(n-1)* pairwise comparisons (Promentilla et al., 2015). A positive $\boldsymbol{\lambda}$ indicates a consistent fuzzy pairwise comparison matrix wherein a $\boldsymbol{\lambda = 1}$ suggests perfect consistency in preserving the order of preference intensities.

Step 4. Compute the global priority weights of these alternatives with respect to the goal. For example, given the decision structure in Figure 1, the global priority weights can be computed as follows:

$$W_{AG} = W_{AC}W_{CG} \tag{3}$$

where: W_{AG} = is matrix containing the global priority weights of alternative with respect to goal. In this study, it is a column vector of order *m* which corresponds to the number of alternatives in the decision structure. The W_{CG} is the matrix containing the importance weights of criteria with respect to goal. It is a column vector of order *n* which corresponds to the number of criteria in the decision structure. The W_{AC} is the matrix containing the priority weights of alternatives with respect to each criterion. It is an array of *m* rows and *n* columns representing the number of alternatives and criteria, respectively.

3. Case study

This study considers optimal selection among four aerobic biological treatment processes, namely: (a) Conventional Activated Sludge (CAS) system, (b) Sequencing Batch Reactor (SBR), (c) Integrated Fixed Film Activated Sludge (IFAS) system, and (d) Membrane Bioreactor (MBR). The CAS system is typically considered as the base option and has been one of the most popular systems for municipal and industrial wastewater treatment since 1920s (Tchobanoglous et al., 2003). It involves a suspended growth activated sludge process that utilizes a separate unit for aeration and for settling. The SBR system utilizes a single reactor where all the processes in the CAS take place in sequential order (i.e. fill – and – draw) which was established around 1920s. It is capable of producing excellent effluent quality but suffered in operational aspect. Further developments of the SBR system did not occur until the 1950s and more development took place in the 1970s. IFAS system combines suspended-growth and attached-growth advantages into one system by incorporating an engineered plastic media to an activated sludge system. This technology was developed in the late 1980s and further commercialized from year 2000 onwards (Hammer and Hammer, 2005). The MBR on the other hand utilizes a microporous membrane for solid-liquid separation in place of a secondary sedimentation tank. This was introduced in the late 1960s. However, it was only further developed from 1990 onwards, especially in Canada, Japan & UK (van der Roest et al., 2002).

These four aerobic biological systems are evaluated based on three criteria, namely: (a) economic aspect, (b) environmental aspect, and (c) technical aspect. Each criterion has sub-criteria as presented in Figure 3. Capital cost and operating cost fall under economic aspect. Capital cost refers to the cost of initially putting up the whole system which typically includes the civil works and electro-mechanical works. On the other hand, operating costs includes the yearly cost incurred in maintaining the system. Environmental aspect considers the following sub-criteria: (a) treated effluent quality in terms of meeting or exceeding the specified discharge standard, (b) ability to adjust to variable hydraulic and pollutant loading, (c) ability to cope with oil ingress particularly that PRWW typically contains this parameter, and (d) space requirement, which could be a site-specific problem. Technical aspect on the other hand involves the following sub-criteria: (a) pre-treatment requirement which is dependent on succeeding unit processes, e.g. MBR would require fine screening so as not to prevent severe membrane fouling, (b) secondary clarifier requirement would normally be an issue if there's not enough space available for a WWTP, thus a compact MBR which does not require a secondary clarifier is favourable in areas with land limitation, (c) reliability and validity of technology refers to the historical robustness of the process, e.g. MBR is quite new in the industry compared to CAS, and (d) complexity to operate and control.

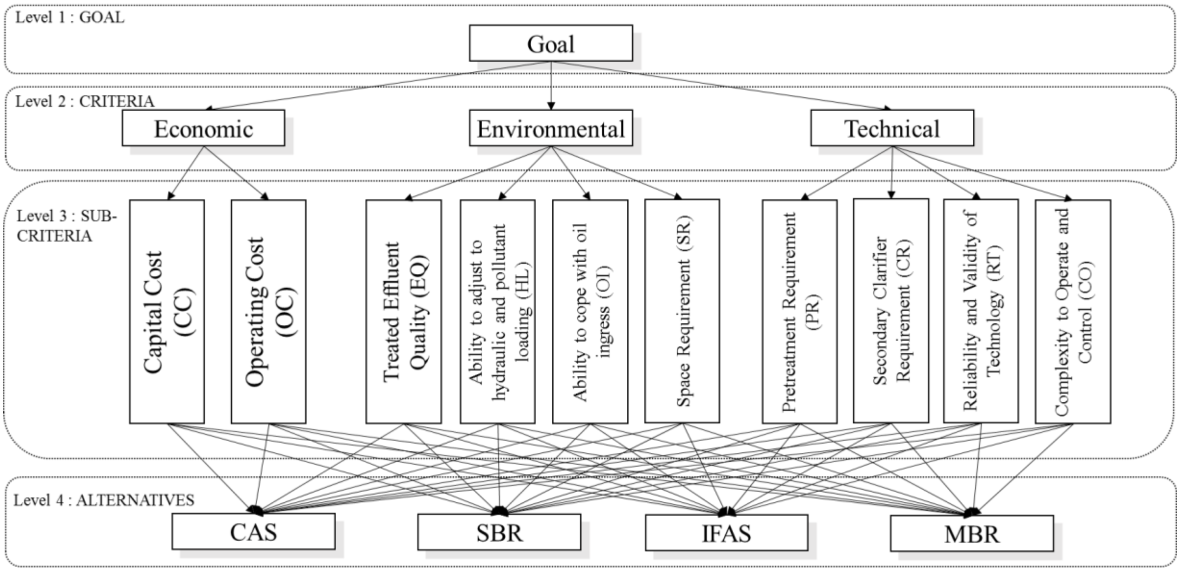

Figure 3: Decision structure for the selection of aerobic biological treatment processes for PRWW

A pool of experts and stakeholders were involved in the pairwise comparison among criteria and sub-criteria in order to rate the relative importance of each elements in the decision structure. As shown in Table 1, environmental aspect has the highest importance weight while technical aspect has the least weight. Among the sub-criteria, operating cost (CC) has the highest global weights followed by treated effluent quality (EQ). The performance scores of all alternatives with respect to each sub-criterion are presented in Table 2. This also shows the overall scores of the alternatives indicating that SBR is the most preferred system closely followed by CAS. IFAS and MBR do not differ that much from each other and are considered to be the least preferred among the options mainly due to the cost of operating these two systems.

Table 1: Relative weights of criteria and sub-criteria

Criteria	Local weights	Sub-criteria	Local weights	Global weights
Economic	0.3916	Capital Cost (CC)	0.44	0.1704
		Operating Cost (OC)	0.56	0.2212
Environmental	0.4212	Treated effluent quality (EQ)	0.46	0.1958
		Ability to adjust to variable hydraulic and pollutant loading (HL)	0.23	0.0963
		Ability to cope with oil ingress (OI)	0.19	0.0787
		Space requirement (SR)	0.12	0.0504
Technical	0.1872	Pre-treatment requirement (PR)	0.27	0.0503
		Secondary clarifier requirement (CR)	0.18	0.0340
		Reliability and validity of technology (RT)	0.39	0.0723
		Complexity to operate and control (CO)	0.16	0.0305

Table 2: Normalized performance scores with respect to each sub-criterion and the overall score of alternatives

Alternatives	CC	OC	EQ	HL	OI	SR	PR	CR	RT	CO	Overall
CAS	0.395	0.403	0.082	0.100	0.175	0.071	0.289	0.241	0.375	0.360	0.260
SBR	0.413	0.403	0.264	0.232	0.339	0.156	0.289	0.325	0.375	0.361	0.332
IFAS	0.130	0.132	0.249	0.365	0.217	0.336	0.289	0.108	0.125	0.196	0.203
MBR	0.062	0.061	0.405	0.303	0.269	0.437	0.133	0.325	0.125	0.082	0.205

To determine how the variations in the weight of economic, environmental and technical criteria affect the ranking of the four treatment alternatives, sensitivity analyses were performed with respect to these main criteria. Figure 4 illustrates the results from the sensitivity analysis. When economic aspect is not considered or given lesser weights, MBR is the dominant alternative followed by SBR. In contrast when economic is the only criterion, the most preferred treatment alternative is SBR followed by CAS, whereas IFAS and MBR are the least preferred. Note that the points of intersections indicate where rank reversals will start to occur. For example, rank reversal of MBR and SBR for first and second positions occurred when economic increased from zero to about 0.04 (Figure 4a). At about 0.25 for the weight of economic criterion, another rank reversal was observed between MBR and CAS for the second and third preferred alternatives. As for the sensitivity of ranking on the environmental criterion, reversal of SBR and MBR was observed at weight equal to about 0.74 for the first and second ranks (Figure 4b). On the other hand, from Figure 4c, it can be seen that ranking is not sensitive with respect to the technical criterion since the ranking of the two most preferred alternatives did not change at varying weights.

4. Conclusions

Four aerobic biological systems are compared against a set of criteria wherein the economic aspect, particularly the operating cost, has the highest weight. The Group Fuzzy AHP model showed that SBR is the most preferred option with regard to aerobic biological system for the treatment of petroleum refinery wastewater. The sensitivity analysis indicates that rankings of the alternatives were influenced largely by the economic and environmental criteria. In contrast, the model results are relatively robust with respect to the varying weights of technical criterion. Future work will incorporate uncertainty analysis in the decision model though Monte Carlo simulation.

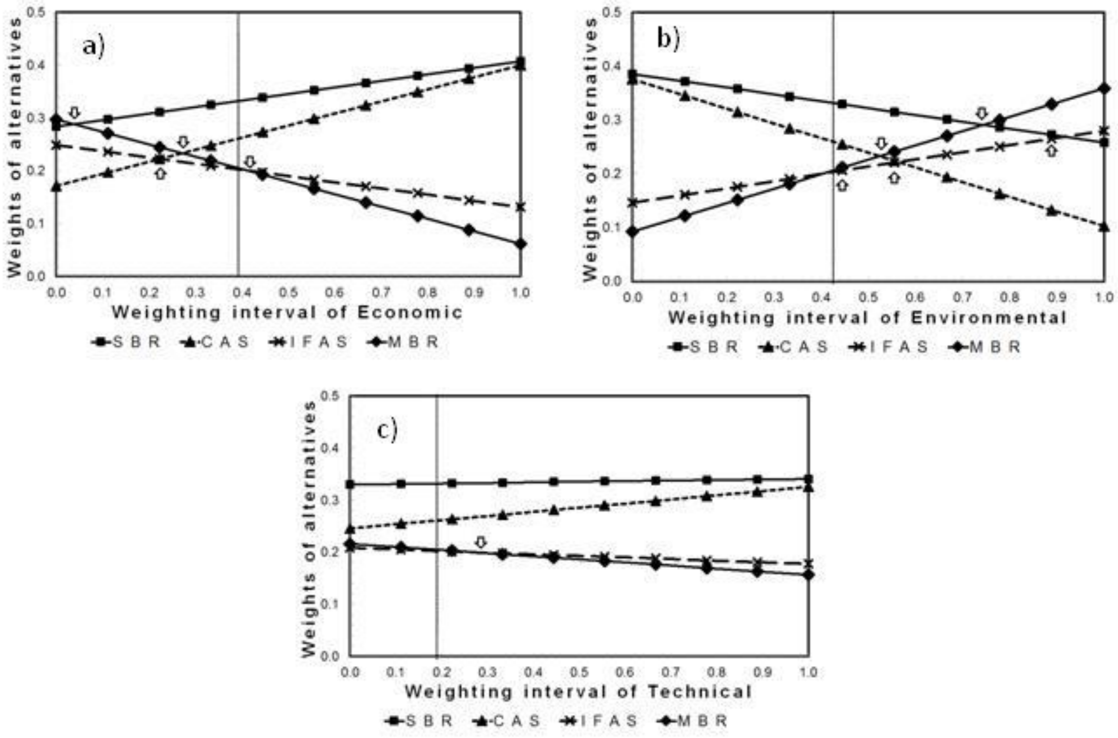

Figure 4: Sensitivity Analysis with respect to weighting of a) Economic Aspect, b) Environmental Aspect, and c) Technical Aspect.

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