Selection of Optimum Biological Nutrient Removal (BNR) System for Urban Areas' Wastewater Treatment Plants using Analytical Network Process (ANP)

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Abstract: Eutrophication is caused by excessive nutrient concentration in the bodies of water due to anthropogenic sources such as wastewater effluent. In order to address this, biological nutrient removal (BNR) systems in wastewater treatment plants (WTP) were developed. In the Philippines, BNR systems are yet to be applied in WTPs since the government just recently started the implementation of the new effluent standards including the control of nutrient content in the wastewater effluent. However, wastewater treatment systems are complex due to various factors such as design, costs, space requirement and treatment efficiency. With that, a complex decision making problem is established to select the best BNR system considering multi-criteria. This study will focus on the selection of the optimum BNR system that can be applied in the urban areas' WTPs using Analytical Network Process (ANP) considering the following criteria: 1) Economic aspect; 2) Technical aspect; 3) Environmental Aspect; 4) Space Requirement. The following alternatives are evaluated: 1) 3 Stage Pho-redox (A2O); 2) 5 Stage Bardenpho (5BP); 3) University of Cape Town (UCT); 4) Virginia Initiative Plant; 5) Sequencing Batch Reactor (SBR); 6) Membrane Bioreactor (MBR). Overall priority weights results showed that the SBR is the optimum BNR system to be installed in the WTPs in urban areas. A sensitivity analysis is performed for every criterion with respect to the goal to determine the ranking stability of the alternatives with varying priority weights of criteria.

Key Words: biological nutrient removal; wastewater treatment; analytical network process; ANP

1. INTRODUCTION

Nutrients specifically nitrogen (N) and phosphorus (P) are needed in order to sustain and improve growth of plants both in land and in water. Nutrients in the form of fertilizers create beneficial effects to agricultural lands. However, excess nutrient concentration in the water bodies causes adverse effects to the aquatic biodiversity that leads to eutrophication. Eutrophication is the accelerated growth rate of aquatic plants and algae due to increased availability of nutrients and other factors such as sunlight and carbon dioxide. Algal bloom and excessive growth of aquatic plants limit light penetration and deplete dissolved oxygen which is also needed to support aquatic organisms (Chislock et al, 2013). Nonpoint sources such as storm water run-off and point sources such as wastewater effluent and agricultural water run-off cause the increase in nutrient concentration. With that, efforts are being made to address this problem by researchers and industries involved.

Other countries have already implemented the monitoring of nutrient content in water and wastewater discharges especially in their wastewater treatment plants (WTP). In order to control and remove nutrient concentration in the wastewater effluent, different technologies were developed including biological nutrient removal (BNR) systems and nutrient recovery systems (The Cadmus Group, 2009; Kleeman et al, 2015; Estrada-Arriaga et al, 2016).

Current domestic and industrial WTPs in the Philippines do not implement BNR systems yet because nutrient content in effluents were not being monitored. However, the Department of Environment and Natural Resources (DENR) released a new Department Administrative Order DAO 2016-08 last May 2016 indicating the new water quality guidelines and general effluent standards starting 2016 (DENR, 2016). Among the changes is the addition of parameters to be monitored and controlled including ammonia-N (NH3-N), Nitrate-N (NO3-N) and Phosphorus as Phosphates. The government gave a grace period of not more than five years to comply with the new DAO. Because of that, WTPs need to upgrade their current system that includes installation of BNR systems in order to comply with the new standards.

The selection of the best BNR system to be installed in the Philippines is now the challenge to stakeholders especially in WTPs located in urban areas. Water and wastewater treatment systems are complex and dynamic since treatment is influenced by interactions of factors such as water quality, regulatory requirements, consumer and environmental concerns, construction challenges, operational constraints, and economic feasibility (Hamouda et al, 2009). According to USEPA (The Cadmus Group, 2009), the barriers in the implementation of BNR system are costs, limitations on physical expansion, state resources, increased carbon footprint, and advanced operations and control. Industries with WTPs are now faced with a decision making problem to evaluate the best BNR alternative considering multiple criteria.

This study will focus on the selection of the optimum BNR system that can be applied in the urban areas' WTP using Analytical Network Process (ANP), a Multi-criteria Decision Analysis (MCDA) tool. MCDA is a tool that can provide decision support to complex and multifaceted problems considering the interconnection of various factors (Kiker et al, 2005; Hamouda et al, 2009; Wang et al, 2009). Common MCDA methods used in different environmental decision making problems are Multiattribute Utility Theory (MAUT), Analytical Hierarchical Process (AHP) and Analytical Network Process (ANP). AHP utilizes pairwise comparisons of all criteria and alternatives to institute relationships within the hierarchical problem structure. ANP is the generalization of AHP which considers the interactions and dependence between the elements of clusters or networks (Saaty, 1977).

2. METHODOLOGY

The first step to rank the alternatives using ANP is to setup the network structure to represent the complex decision making problem. Fig. 1 shows an example of a decision network structure of a complex problem. The network structure is established with top to bottom hierarchy followed by feedback from alternatives to criteria, inner dependence of all criteria, and feedback control loop as represented by the direction of the arrows and arc. The feedback control loop indicates that all the elements in the structure are important and influenced by the goal element (Promentilla et al, 2006a).

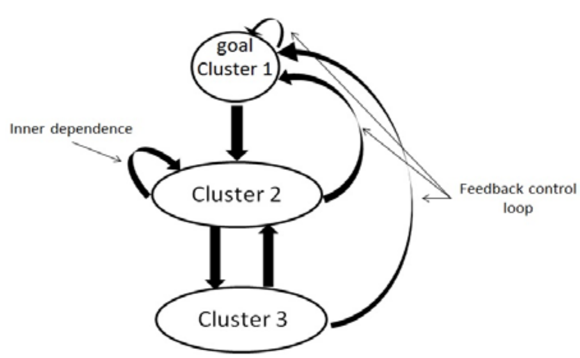

Fig. 1. An example of ANP network structure

The second step is to gather pairwise comparisons of all interacting elements with respect to elements of another cluster or, with respect to elements within the cluster when inner dependence is evaluated. The pairwise comparison matrix is then computed using the eigenvector method thus the priority weights are the eigenvectors of the resulting matrix. The inconsistency of the value judgments is evaluated using the consistency ratio (CR) where a CR value of more than 0.10 may not be preferred.

The third step is to calculate for the overall priority weights of the alternatives using the concept of supermatrix with the aid of SuperDecisions 2.8 software. The initial supermatrix or the unweighted matrix is composed of eigenvectors obtained from the previous step. This will be normalized by the column sum resulting to weighted supermatrix. The matrix will then be raised to large powers until it converges into an answer which establishes a Limit Matrix (Promentilla et al, 2006b). The resulting answers are then normalized per cluster. Finally, a sensitivity analysis is conducted to determine the ranking stability of the alternatives with varying criteria weights. Fig. 2 shows the summary of methodology in utilization of ANP tool.

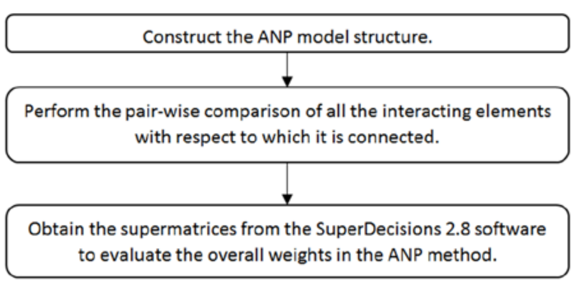

Fig. 2. Summary of the method

3. CASE STUDY

This study evaluates the best biological nutrient removal system to be installed in existing wastewater treatment plants (WTPs) located in the urban areas. The four criteria that are found to be important in the selection are economic aspect (EC), technical aspect (TL), environmental aspect (EN), and space requirements (SR). EC considers lower capital costs (i.e. installation costs, etc.) and operating costs. TL considers the overall performance of the process and the technical capability of the assigned personnel. EN is being evaluated by the effluent quality especially but not limited to lower nitrogen and phosphorus concentration in the effluent. The new DAO 2016-08 added nitrogen as ammonia and nitrates, and phosphorus as phosphates, among others as the parameters to be controlled and monitored. In general, the effluent quality must pass the standard. However, for the comparison of elements with respect to the environmental aspect, emphasis must be given to the least nutrient content in the effluent. SR refers to the expansion of the WTP when the BNR is installed. Since there are already existing WTPs in cities, addition of space consuming technology such as BNR systems may require physical expansion of the plant. In this criterion, the priority must be given to the alternative with lesser space requirement.

The following are the six alternatives to be evaluated: 3 stage pho-redox (A2O), 5-stage Bardenpho (5BP), University of Cape Town (UCT), Virginia Initiative Plant(VIP), Sequencing Batch Reactor (SBR) and Membrane Bioreactor (MBR). A2O is a conventional activated sludge system involving anaerobic-anoxic-aerobic zone. In order to enhance denitrification, the nitrate-rich liquor is recycled from the aerobic zone to the start of the anoxic zone. The return activated sludge (RAS) is returned in the anaerobic zone. The 5BP consists of five stages with anaerobic-anoxic-aerobic-anoxic-aerobic zones. The nitrate-rich liquor is recycled to the first anoxic stage from the first aerobic stage while the RAS is recycled to the beginning of the anaerobic stage from the clarifier. UCT also consists of three stages, anaerobic-anoxic-aerobic stage. However, the RAS is returned from the clarifier to the anoxic stage while the nitrate-rich liquor is recycled from the aerobic stage to the anoxic stage (The Cadmus Group, 2009). VIP having the same anaerobic-anoxic-aerobic stages recycles its RAS to the anoxic stage where denitrification occurs before entering the anaerobic stage (Mayor et al, 2004). SBR is a batch operation of anaerobic-anoxic-aerobic stages through adjustment of mixing and aeration (The Cadmus Group, 2009). MBR utilizes membranes for the nutrient removal (Silva et al, 2011).

Having the aforementioned set of criteria and six possible alternatives to be considered for the selection of the best BNR system, the complex decision making problem can be summarized in a network structure shown in Fig. 3. Since the selection of the BNR system is influence by a cluster of criteria, it is represented by an arrow from the goal cluster to the criteria cluster. However, the evaluation of these criteria may be also influenced by the other criteria, thus the inner dependence represented by the arc loop must also be considered in the decision making problem. The preferred alternative with respect to each criterion is also being assessed as represented by the arrow from the criteria cluster to the alternative cluster. On the other hand, the evaluation of each alternative may also be influenced by the dominating criteria, thus the feedback is also considered as represented by the arrow from the alternative cluster to the criteria cluster. The feedback control loop is represented by the red arcs pointing to the goal cluster from the goal, criteria and alternative cluster which indicates that all the elements in the structure are influenced by the goal.

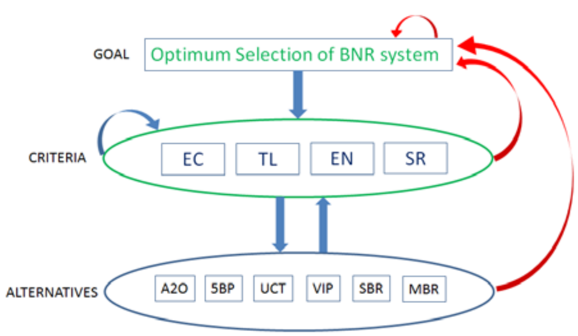

Fig. 3. ANP network structure for the selection of best BNR systems in urban areas

Three experts from the academe participated in the provision of value judgments through pairwise comparisons of the elements in the clusters. In order to come up with an aggregated pairwise comparison matrix, the geometric mean of the value judgments for each pairwise comparison element was calculated.

The aggregated data are encoded in the SuperDecisions 2.8 software which utilizes the supermatrix concept to arrive at an answer. The software generated the unweighted supermatrix, shown in Table 1, which contains the eigenvectors from the pairwise comparison matrix. The weighted supermatrix is also generated as seen in Table 2, wherein values in the unweighted supermatrix are normalized using column sum. The stochastic values in the weighted supermatrix are raised in large powers to converge to a limit and provide dominance weight of influence of each element. The resulting limit matrix is presented in Table 3.

Table 4 shows the overall relative importance of criteria in the selection of the optimum BNR system. After the normalization of weights in the limit supermatrix for the criteria cluster, results show that the economic aspect is the most important factor among the set of criteria followed by environmental aspect, technical aspect, and space requirement.

Table 1. Unweighted Supermatrix

Unweighted Supermatrix		Alternatives						Criteria				Goal
		A2O	5BP	UCT	VIP	SBR	MBR	EC	TL	EN	SR	Optimum
Alternatives	A2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3207	0.3196	0.0847	0.1368	0.0000
	5BP	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1015	0.1830	0.1034	0.0334	0.0000
	UCT	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0727	0.1112	0.1116	0.0496	0.0000
	VIP	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0683	0.0881	0.1351	0.0546	0.0000
	SBR	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3854	0.2447	0.1086	0.2373	0.0000
	MBR	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0514	0.0533	0.4566	0.4883	0.0000
Criteria	EC	0.3041	0.3758	0.2162	0.2334	0.2020	0.3244	0.5253	0.1819	0.3897	0.5656	0.2115
	TL	0.2550	0.2149	0.2195	0.2674	0.2955	0.1735	0.1681	0.4891	0.2577	0.1628	0.2312
	EN	0.1738	0.1590	0.3441	0.3187	0.2405	0.2653	0.1189	0.2081	0.2297	0.0937	0.3446
	SR	0.2672	0.2503	0.2202	0.1805	0.2621	0.2368	0.1877	0.1210	0.1229	0.1779	0.2127
Goal	Optimum	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

Table 2. Weighted Supermatrix

Weighted Supermatrix		Alternatives						Criteria				Goal
		A2O	5BP	UCT	VIP	SBR	MBR	EC	TL	EN	SR	Optimum
Alternatives	A2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1069	0.1065	0.0282	0.0456	0.0000
	5BP	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0338	0.0610	0.0345	0.0111	0.0000
	UCT	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0242	0.0371	0.0372	0.0165	0.0000
	VIP	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0228	0.0294	0.0450	0.0182	0.0000
	SBR	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1285	0.0816	0.0362	0.0791	0.0000
	MBR	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0171	0.0178	0.1522	0.1628	0.0000
Criteria	EC	0.1520	0.1879	0.1081	0.1167	0.1010	0.1622	0.1751	0.0606	0.1299	0.1885	0.1058
	TL	0.1275	0.1075	0.1098	0.1337	0.1477	0.0868	0.0561	0.1630	0.0859	0.0543	0.1156
	EN	0.0869	0.0795	0.1720	0.1594	0.1202	0.1327	0.0396	0.0694	0.0766	0.0312	0.1723
	SR	0.1336	0.1252	0.1101	0.0902	0.1310	0.1184	0.0626	0.0403	0.0410	0.0593	0.1064
Goal	Optimum	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000	0.3333	0.3333	0.3333	0.3333	0.5000

Table 3. Limit Matrix

Limit Matrix		Alternatives						Criteria				Goal
		A2O	5BP	UCT	VIP	SBR	MBR	EC	TL	EN	SR	Optimum
Alternatives	A2O	0.0316	0.0316	0.0316	0.0316	0.0316	0.0316	0.0316	0.0316	0.0316	0.0316	0.0316
	5BP	0.0155	0.0155	0.0155	0.0155	0.0155	0.0155	0.0155	0.0155	0.0155	0.0155	0.0155
	UCT	0.0126	0.0126	0.0126	0.0126	0.0126	0.0126	0.0126	0.0126	0.0126	0.0126	0.0126
	VIP	0.0126	0.0126	0.0126	0.0126	0.0126	0.0126	0.0126	0.0126	0.0126	0.0126	0.0126
	SBR	0.0354	0.0354	0.0354	0.0354	0.0354	0.0354	0.0354	0.0354	0.0354	0.0354	0.0354
	MBR	0.0352	0.0352	0.0352	0.0352	0.0352	0.0352	0.0352	0.0352	0.0352	0.0352	0.0352
Criteria	EC	0.1241	0.1241	0.1241	0.1241	0.1241	0.1241	0.1241	0.1241	0.1241	0.1241	0.1241
	TL	0.1051	0.1051	0.1051	0.1051	0.1051	0.1051	0.1051	0.1051	0.1051	0.1051	0.1051
	EN	0.1146	0.1146	0.1146	0.1146	0.1146	0.1146	0.1146	0.1146	0.1146	0.1146	0.1146
	SR	0.0848	0.0848	0.0848	0.0848	0.0848	0.0848	0.0848	0.0848	0.0848	0.0848	0.0848
Goal	Optimum	0.4286	0.4286	0.4286	0.4286	0.4286	0.4286	0.4286	0.4286	0.4286	0.4286	0.4286

Table 4. Relative importance of criteria

Criteria	Weight
EC	**0.14481**
TL	0.12263
EN	0.13364
SR	0.09892

The summary of the normalized weights of alternatives is presented in Table 5. Results show that the optimum BNR system to be installed in the WTPs located in urban areas is SBR followed by MBR, A2O, 5BP, VIP and UCT. However, it can be observed that the weights of SBR and MBR have almost 0.001 difference. A sensitivity analysis may show the stability of this rating.

Table 5. Overall priority weights of alternatives

Alternatives	weight
A2O	0.22099
5BP	0.10854
UCT	0.08797
VIP	0.08830
SBR	**0.24758**
MBR	0.24662

The summary of the normalized weights of alternatives is presented in Table 5. Results show that the optimum BNR system to be installed in the WTPs located in urban areas is SBR followed by MBR, A2O, 5BP, VIP and UCT. However, it can be observed that the weights of SBR and MBR have almost 0.001 difference. A sensitivity analysis may show the stability of this rating.

The ranking of alternatives may vary depending on the priority weights of the criteria with respect to goal. In order to determine the stability of the rankings with varying weights of criteria, a sensitivity analysis is performed for every criterion.

The sensitivity analysis for EC in Fig. 4 shows that when the priority weight of EC is less than 0.21, MBR dominates the ranking. However, when the weight of EC is increased from 0.21, SBR dominates and MBR gradually decreases its rank. It is observed in Fig. 5 that when TL is not prioritized, MBR is ranked first. When the weight of TL is 0.20 until 0.58, SBR is ranked first. A2O becomes the best alternative when the weight of TL is varied with any value more than 0.58. The sensitivity analysis for EN presented in Fig. 6 shows that a priority weight of less than 0.33, SBR is the best alternative. A weight of more than 0.33 would make MBR as the best alternative. Shown in Fig. 7 is the sensitivity analysis for SR wherein SBR dominates the ranking when SR is not prioritized until a priority weight of 0.20. Assigning any priority weight value of more than 0.20 would result to preference of MBR.

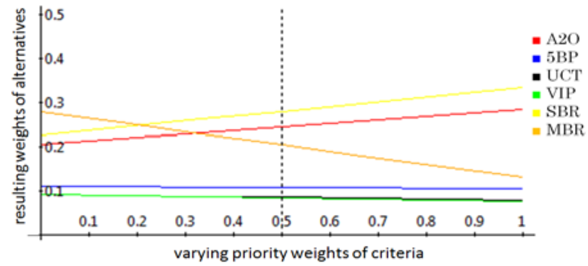

Figure 4. Sensitivity Analysis for Economic Aspect

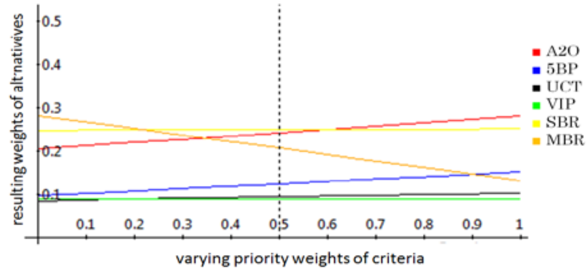

Figure 5. Sensitivity Analysis for Technical Aspect

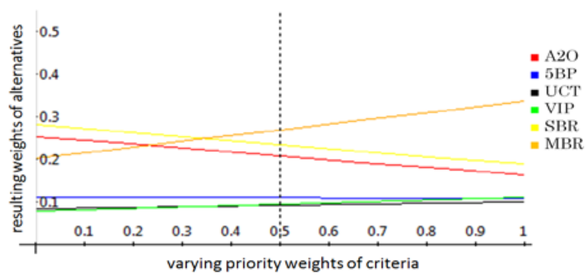

Figure 6. Sensitivity Analysis for Environmental Aspect

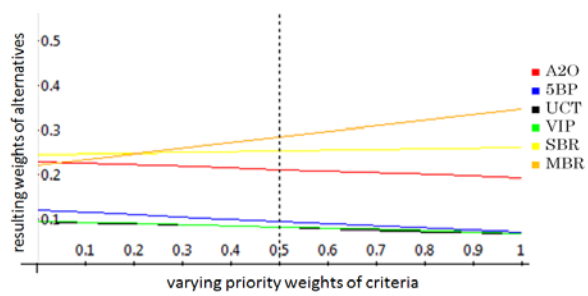

Figure 7. Sensitivity Analysis for Space Requirements

Utilization of ANP tool in decision-making problems may provide objective results. However, a certain degree of subjectivity may be incorporated with value judgments from experts and stakeholders. Thus, elicitation of judgments from various sectors may improve objectivity. In this case study, value judgments are only taken from the experts in the academe. Since BNR systems are not yet implemented in industries in the Philippines, stakeholders cannot provide objective value judgments yet. They may be able to provide priority weights for the criteria but limited knowledge on the alternatives may affect their judgments.

4. CONCLUSION

Among the six alternatives evaluated using ANP as the decision making tool, the optimum BNR system for WTPs in urban areas is the sequencing batch reactor followed by membrane bioreactor. Furthermore, the most important criterion for the selection of the best BNR system is the economical aspect followed by the environmental aspect. The sensitivity analysis shows that the rankings are influenced by changes in the priority weights of all criteria.

5. ACKNOWLEDGMENT

C.M.P. is supported by the Department of Science and Technology - Engineering Research and Development for Technology (ERDT) Program.

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