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Analytical Hierarchy Process in Concept Selection of Wastewater Treatment Plant

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Authors' contributions

This work was carried out in collaboration between all authors. Author ILN involved in study design, wrote the protocol and first draft of the manuscript. Authors OB and LOU managed the analyses of the study and literature survey. All the authors read and approved the final manuscript.

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ABSTRACT

In most Engineering designs concept selection is a critical stage of the design process. This study focuses on the concept selection for the design of a proposed wastewater treatment facility for a settlement (Forcados-Yokri) located in Burutu Local Government Area (LGA), Nigeria. Three wastewater treatment concepts (Completely Mixed Activated Sludge (CMAS), Sequencing Batch Reactor (SBR) and Up-flow Anaerobic Sludge Blanket (UASB)) were proposed. Also, based on seventeen sub-criteria which were grouped into four major criteria (Environmental Impact, Social Impact, Operability and Economic/schedule), Analytical Hierarchy Process (AHP) was applied for the selection of the best concept. Among the seventeen sub-criteria were ten boundary conditions generated with respect to the study area and the acceptable effluent discharge standards (FEPA, DPR-EGASPIN & WHO).The parameter weight was done with respect to data from literature and project stakeholders (interested parties involved in the selection process). The total relative

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score with respect to the ten sub-criteria (which also served as boundary condition) for CMAS, SBR and UASB were correspondingly 9.11, 30.40 and 25.63 respectively. This makes SBR the recommended choice of the three proposed wastewater treatment concepts.

Keywords: Engineering designing; Burutu local government area; completely mixed activated sludge (CMAS), sequencing batch reactor (SBR) and Up-flow anaerobic sludge blanket (UASB).

1. INTRODUCTION

Concept selection is the phase in concept design usually in Engineering where the engineer (designer) evaluates various concepts pertaining to a proposed design but with respect to the expected need of the client or costumer. It is a decision making stage which involves comparing the relative strength and weakness of the proposed concepts [1]. Among other concept selection methods such as Pugh's concept scoring, Analytical Hierarchy Process (AHP), fuzzy AHP, in-equivalents methods, flexible design concept selection, and Quality Function Deployment (QFD), AHP and Pugh's concept scoring methods are the most commonly adopted approaches in Industries. The difference between AHP and the Pugh's concept scoring methods is that the AHP is a more mathematical version of the concept scoring method.

Areas of application of AHP in concept selection include, software selection known as Muti-media Authorizing System [2]. Al Harbi [3] employed AHP in the selection of the best contractor in a project management scenario; furthermore, Khalid et al. [4] worked on a Component Object Model based spatial decision support system for the choice of siting industrial facility applying AHP. He also cited the work of Korpela and Tuominen published in 1996 who also applied the concept of AHP for the processes involved in the siting of a warehouse. Bovwe et al. [5] also, applied AHP into the selection and modelling of experts' opinions as per best options for efficient solid waste management for Nigeria.

With respect to this study, three concept options were considered for the selection of a proposed wastewater treatment plant. These concepts are:

i) Completely Mixed Activated Sludge (CMAS) system;
ii) Sequencing Batch Reactor (SBR) system; and
iii) Up-flow Anaerobic Sludge Blanket (UASB) system.

1.1 Option 1- Completely Mixed Activated Sludge (CMAS) System

This method is over a hundred years old and it is the most widely used method of biological wastewater treatment around the world [6,7]. Basically there are four process variations of activated sludge. These include:

i) Conventional activated sludge;
ii) Extended aeration;
iii) Completely mixed activated sludge; and
iv) The contact stabilization process.

In general, the basic activated sludge process consists of several interrelated components such as:

i) An aeration tank where the biological reactions occurs;
ii) An aeration source that provides oxygen and mixing;
iii) A tank, known as the clarifier, where the solids settle and are separated from the treated wastewater; and
iv) A means of collecting the solids either to return them to the aeration tank, (return activated sludge) or to remove them from the process (waste activated sludge).

1.2 Option 2- Sequencing Batch Reactor (SBR) System

The sequencing batch reactor (SBR) is considered a fill-and-draw activated sludge system. The processes of equalization, aeration, and clarification are all achieved in the same tank, unlike a conventional activated sludge system, in which the same processes are accomplished in separate tanks. Wastewater is added to the tank, treated to remove undesirable components, and then discharged. SBR systems consist of five common steps carried out in sequence [8,9]:

i) Fill;
ii) React (aeration);
iii) Settle (sedimentation/clarification);

iv) Draw (effluent decantation); and
v) Idle.

1.3 Option 3- Up-flow Anaerobic Sludge Blanket (UASB) System

An Up-flow anaerobic sludge blanket (UASB) reactor is basically a tank that has a sludge bed in which organic material dissolved in the wastewater is degraded, and as a result of this digestion, biogas is produced. Wastewater enters at the bottom of the reactor. At the top, biogas is collected and the effluent of the treated water leaves. At the upper part of the reactor, above the sludge bed, a blanket zone is formed between the water flowing up and the suspended biomass. As reported in literature [10] only one discharge of sludge from a UASB is required per year for a four-metre-high reactor. The UASB are widely used to treat wastewater with a high organic load (treatment of wastewater from food industry is a typical example).

2. STUDY AREA

The study area for this research is limited to a settlement in Yokri, Burutu Local Government Area (LGA), Delta State, Nigeria (coordinate: 5˚21'N 5˚31'E) (see Fig. 1). Burutu LGA lies on the coast of the Niger Delta on the two sides of the Forcados River which is a tributary of the River Niger, about thirty kilometres upstream from the Bight of Benin. In the history of Nigeria, Burutu LGA was among the first region visited by the European and Portuguese traders. The Portuguese traders were predominantly slave traders. This region is marked with rivers such as River Focardos, Mahin River, and the Ramos River which were known by history as slave route Rivers by Queen Elizabeth of Great Britain during the period of treaty with the Spanish government [11]. The people living in this region are mostly of the Ijaw ethnicity.

Fig. 1. Map showing study area for proposed choice for concept installation

3. METHODOLOGY

3.1 Data Collection

Data collected for this study included both primary field survey and secondary data. The primary field survey from the study area included availability of raw material / resources for each proposed option construction, available manpower/know-how, and availability of sufficient land area. The secondary data sources included data from literature on the characteristic features, foot prints, manpower, capital/ operational cost for each proposed concept option.

3.2 Data Analysis

Analytical Hierarchy Process (AHP) which was developed by Thomas Saaty [12] is a multi-criteria decision making tool based on a theory of relative measurement [13]. Since its invention, it has been a tool at the hands of decision makers and researchers; and it is one of the most widely used multiple criteria decision-making tools [14]. The comparison scale as proposed by Saaty in 1987 [15] was used as the rating scale (parameter weighting) by the respondents (experts). Table 1 presents the judgments rating scale.

3.3 Concept Selection Criteria

Based on the three options / concepts, are boundary conditions. These boundary conditions are majorly with regards to regulatory standards such as Federal Environmental Protection Agency (FEPA), Department of Petroleum Resources Environmental Guidelines and Standards for Petroleum Industry in Nigeria (DPR-EGAPSIN) & World Health Organization (WHO), and Environmental terrain (boundary conditions are highlighted in Tables 2 & 3). They influence to a greater percentage the choice for efficient wastewater treatment plant as regards to how best the proposed concept options perform and conform to these standards suiting the proposed environment for installation and operability. The boundary conditions are key to sustainable development and environmental best practice options/design.

The four major criteria as per the boundary conditions used to evaluate the various proposed concepts, are*:*

i) Environmental/Social Impact criteria;
ii) Operability Criteria;
iii) Economic Criteria; and
iv) Schedule Criteria.

The Sub-criteria under each of the various major criteria are as presented in Table 2

3.4 Concepts Ranking

In AHP, the weighting of parameters begins with the pair-wise comparison of criteria and sub-criteria. Eigen-values and Eigen-vectors of the pair wise comparison matrix are used in determining the priority (ranking) of each criteria. Equation (1) presents the structure of a pair-wise comparison *matrix, A.*

Table 1. Comparison/judgment scale

Scale of relative importance	Verbal/logical judgments	Explanations
1	Equally preferred	Two activities contribute equally to the objective
2	Equally to moderately	When a compromise is needed
3	Moderately preferred	Experience and judgments slightly favour one activity over the other
4	Moderately to strongly	When a compromise is needed
5	Strongly preferred	Experience and judgments slightly favour one activity over the other
6	Strongly to very strongly	When a compromise is needed
7	Very strongly preferred	An activity is strongly favoured, and its dominance is demonstrated in practice
8	Very strongly to extremely	When a compromise is needed
9	Extremely preferred	The evidence favouring one activity over another is of highest possible order of affirmation

Source: Saaty (2008)

Table 2. Concepts selection criteria

S/No.	Major criteria	Sub-criteria
1.	Environmental/Social impact	Effluent quality[±] Reduced odour production[±] Reduced amount of sludge yield[±] Reduced land area required (foot print) Usefulness of by-product Local availability of resources
2.	Operability	Reduced number of reactors/units Reduced energy requirement Reduced sludge dislodging rate/interval Flexibility/ruggedness (adaptability to shock) [±] Equipment reliability[±] Ease of operation/maintenance/minimal human intervention[±]
3.	Economic	Reduced operating/maintenance cost[±] Increased capital cost
4.	Schedule	Schedule for proposed execution[±] Portability[±] Constructability[±]

[±]*These are the boundary conditions with respect to the 4 major criteria*

$$A = \begin{pmatrix} 1 & a_{12} & \cdots & a_{1n} \\ \frac{1}{a_{12}} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \cdots & 1 \end{pmatrix} \quad (1)$$

For illustration, the pair-wise comparison matrix for the sub-criteria – "Effluent Quality" is as given:

$$A = \begin{array}{c} \\ CMAS \\ SBR \\ UASB \end{array} \begin{pmatrix} CMAS & SBR & UASB \\ 1 & 0.5 & 0.333 \\ 2 & 1 & 1 \\ 3 & 1 & 1 \end{pmatrix}_{3\times3} \quad (2)$$

From Equation (2), by dividing each column-entry by its respective column-sum yields the normalized matrix, *A (see Equation 3)*

$$w^{|G|} = \begin{array}{c} \\ CMAS \\ SBR \\ UASB \end{array} \begin{pmatrix} CMAS & SBR & UASB \\ 0166667 & 0.2 & 0.142735 \\ 0.333333 & 0.4 & 0.428633 \\ 0.5 & 0.4 & 0.428633 \end{pmatrix}_{3\times3} \quad (3)$$

From Equation (3), the priority (weight) ranking (see Equation 5) for CMAS, SBR, and UASB with respect to the sub-criteria- "Effluent Quality" is obtained by applying Equation (4) as:

$$w^{[G]} = \left(w_i^{[G]}\right), \qquad where\ w_i^{[G]} = \left(\prod_{j=1}^{n} a_{ij}^{[G]}\right)^{1/n} \qquad i, j \in \{1, n\} \quad (4)$$

For example, consider row-1 of Equation (3), we have:

$$w^{|G|} = \sqrt[n]{\prod_{j=1}^{n} a_{ij}^{|G|}} \quad = \sqrt[3]{(0.16667 \times 0.2 \times 0.142735)} = 0.168$$

The computed value of 0.168 represents row-1 taken as CMAS. Thus, SBR & UASB follow same row-wise computation, see Equation (5). Appendix A presents the parameter weighing of the major, and sub-criteria from literature [16], experts which comprises of delegated representatives from the stakeholders (proponents), and Environmental design team with regards to the installation of the proposed concept option.

$$w^{[G]} = \begin{array}{c} \\ CMAS \\ SBR \\ UASB \end{array} \begin{pmatrix} weight \\ 0.17 \\ 0.39 \\ 0.44 \end{pmatrix} \quad (5)$$

Applying same procedure of the Analytical Hierarchy Process (AHP) as illustrated, Table 3 presents the absolute rating of the major criteria, the sub-criteria and the proposed concepts (CMAS, SBR, and UASB).

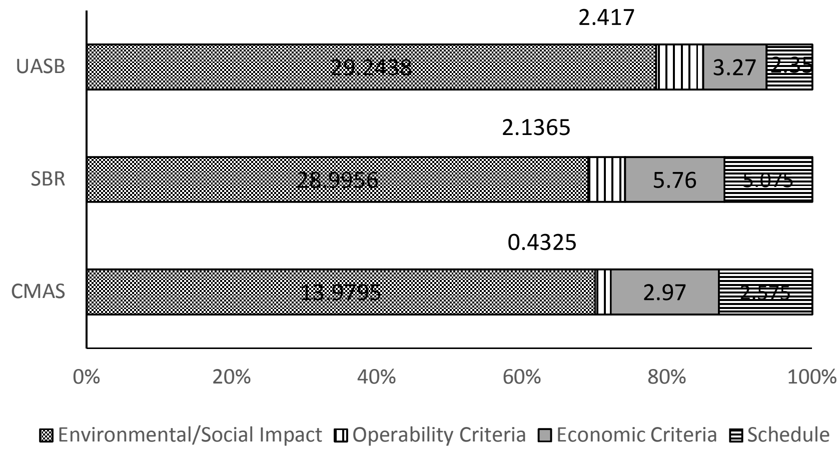

Fig. 2. Major criteria for the boundary conditions

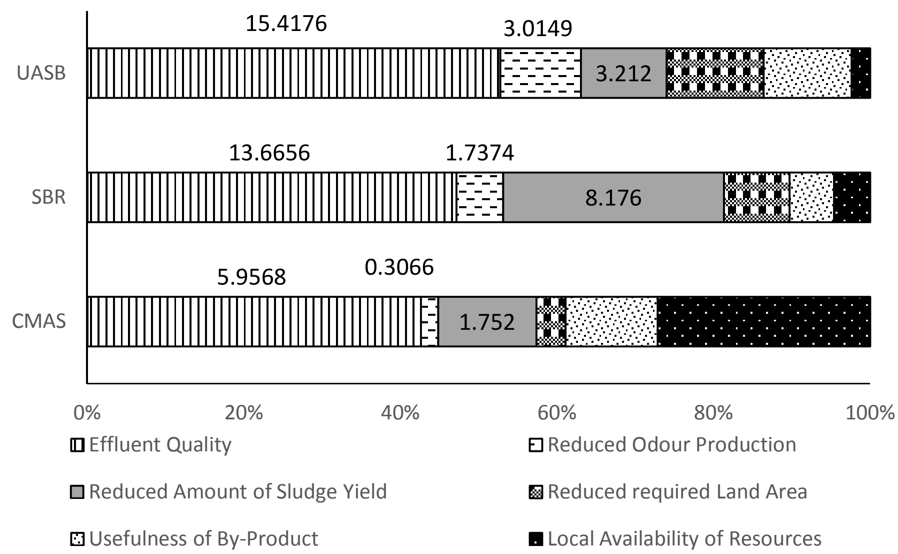

Fig. 3. Environmental/social impact (Major criterion)

The relative comparison of the three concept options with respect to the four major criteria weighting and their influencing sub-criteria is as presented by Figs. 2 – 5, respectively (see Appendix A).

4. DISCUSSION

On applying AHP for the choice of the best concept option taking it on absolute comparison (see Table 3) Environmental/Social Impact turns out to be the highest influential criteria (73%) for the selection of the best and appropriate concept as regards to the establishment of a wastewater treatment facility at the study location with the UASB ranking the highest with regards to the effluent quality which turned out to be the major contributing sub-criteria. This is followed by economic criteria (12%) which has to do with Capital Expenditure (CAPEX) and Operating Expenditure (OPEX) with regards to the concept options. The least influential criterion was the operability criterion (5%). Within the environmental criteria, the expected quality of the effluent when compared relatively with other environmental factors or sub-criteria(see Table 3) ranked the highest concern (48%) that should be taken into consideration in the decision for the best concept option for the wastewater treatment plant. The least concern among the sub-criteria in the Environmental/Social impact criteria tuned out to be the reduction in odour production (7%). Reduced Sludge dislodging rate/interval (28%) was the major influencing concern in the decision making for the choice of the best concept option with regards to operability (see Table 3). This was seconded by minimum required number of reactors/units (27%) and the least influencing concern within the operability criteria was the reliability of the equipment for the construction or installation of the proposed concepts.

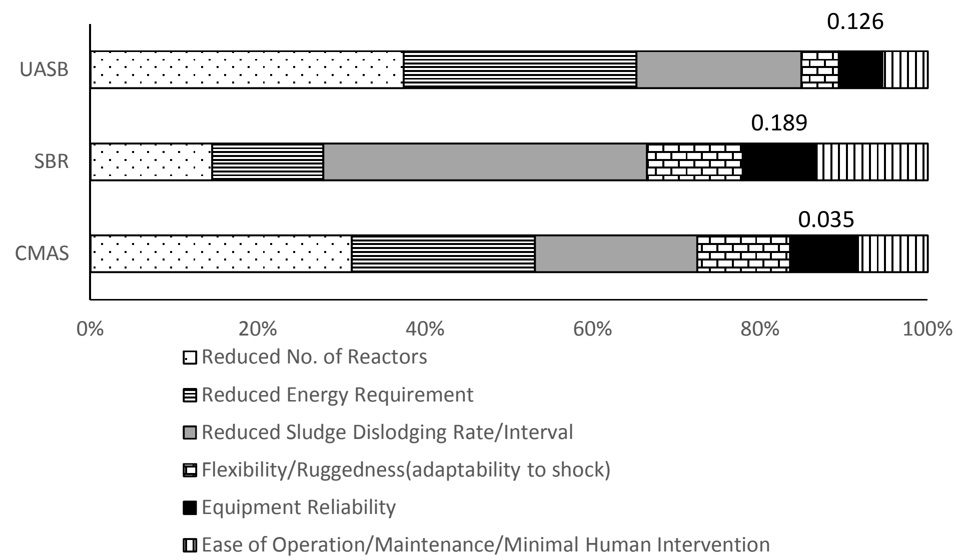

Fig. 4. Operability (Major criterion)

Table 3. Concept analysis output versus the ranking of the criteria

Major criteria	Sub-criteria	CMAS	SBR	UASB
Environmental/	Effluent quality± (48%)	17% (3)	39% (2)	44% (1)*
social impact	Reduced odour production± (7%)	6% (3)	34% (2)	59% (1)
(73%)	Reduced amount of sludge yield± (20%)	12% (3)	56% (1)	22% (2)
	Reduced required land area (foot print) (9%)	8% (3)	37% (2	55% (1)
	Usefulness of by-product (9%)	25%(2)	25% (2)	50% (1)
	Local availability of resources (8%)	65%(1)	23% (2)	12% (3)
Operability	Reduced number of reactors/units (27%)	10% (3)	23% (2)	67% (1)
(5%)	Reduced energy requirement (21%)	9% (3)	27% (2)	64% (1)
	Reduced sludge dislodging rate/interval (28%)	6% (3)	59% (1)	34% (2)
	Flexibility/ruggedness (adaptability to shock) ±	12% (3)	61% (1)	27% (2)
	(8%)	10% (3)	54% (1)	36% (2)
	Equipment reliability± (7%)	8% (3)	63% (1)	29% (3)
	Ease of operation/maintenance/minimal human intervention± (9%)			
Economic	Reduced operating/maintenance cost± (75%)	8% (3)	58% (1)	34% (2)
(12%)	Increase capital cost (25%)	73% (1)	8% (3)	19% (2)
Schedule	Schedule for proposed execution± (25%)	12% (3)	56% (1)	32% (2)
(10%)	Portability± (50%)	9% (3)	64% (1)	27% (2)
	Constructability± (25%)	73% (1)	19% (2)	8% (3)

±These are the boundary conditions with respect to the 4 major criteria
**44% (1) implies a score of 44% which ranks 1st out of 3 concept options*

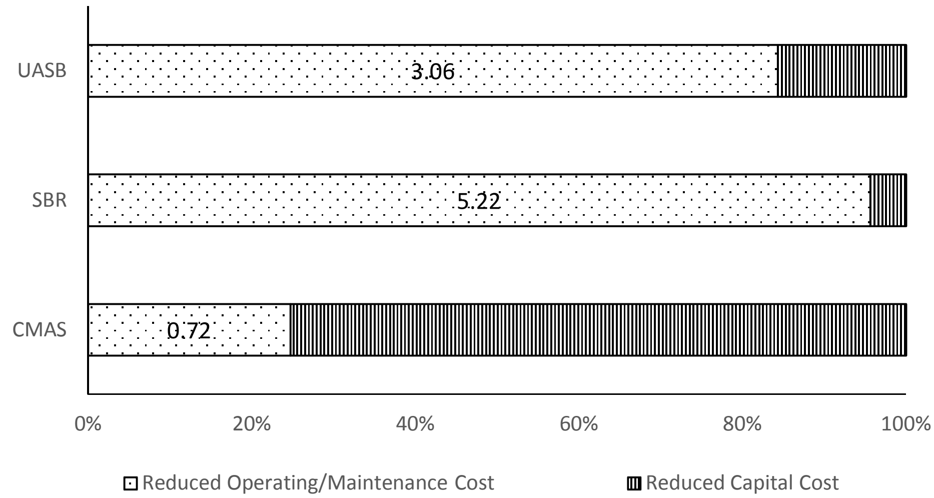

Fig. 5. Economic (Major criterion)

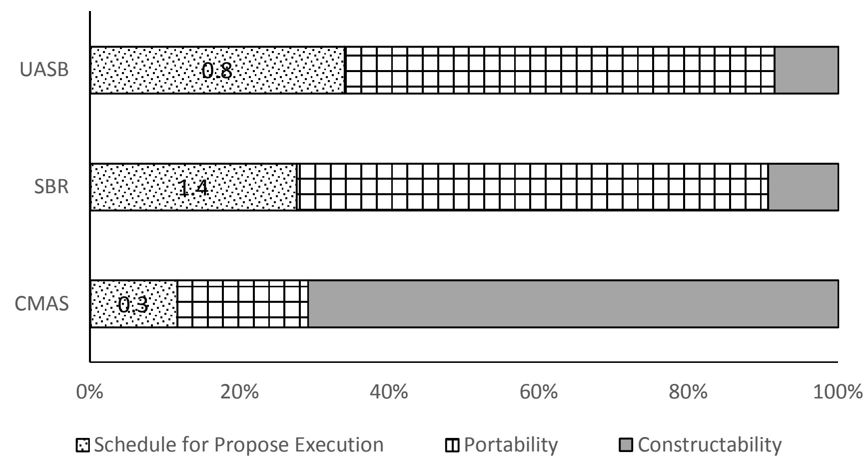

Fig. 6. Schedule (Major criterion)

Furthermore, within the economic criteria it was no surprise that the criterion that has to do with Reduced Operating/Maintenance cost (75%) ranked the highest influencing concern for the best concept option. From the schedule criteria, on applying AHP, the most influencing factor for the choice of the treatment plant is the portability feature or attribute the treatment plant must possess. From the relative comparison of the major criteria and their respective sub-criteria (see Figs. 2 – 5) with respect to the boundary conditions (see Table 3), the proposed three concept options ranked 25.63, 30.40, 9.11 for UASB, SBR and CMAS, respectively. However, when all the 16No. sub-criteria were considered as in Table A1 (see Appendix), the concept options ranked 38, 42, and 20 for UASB, SBR and CMAS, respectively. Thus, SBR ranked first in both boundary conditions (10 Nos) and for the entire sub-criteria (16Nos).

5. CONCLUSION

Based on the results of this study, the following conclusions can be drawn:

i). Given the four major criteria used for the analysis, Environmental/social impact criterion contributes the highest (73%) in influencing the choice for the best concept ranked, while Operability has the least influence (5%).

ii). Taking each major criteria; Effluent quality has the greatest influence on the decision of the concept option with respect to the Environmental/social impact; with respect to operability, the number of required reactor(s) influences the choice for the concept selection to a greater percentage);
iii). Economically, the proposed financial burden to be incurred by each concept during its operation tends to contribute more towards influencing choice of concept with the SBR having the highest weight (5.22) (see Appendix A); and
iv). Finally, with respect to the ease of schedule for proposed concept option, the portability of the concepts influences more as to the choice of what concept with the SBR having the highest weight of 3.2 for portability. Furthermore taking the boundary condition (see Table 3) and the final relative comparison of the concepts the final ranking of the proposed three concept are 25.63, 30.40, 9.11 for UASB, SBR and CMAS, respectively.
v). It is clear that the score for SBR is by far better than UASB; the difference appears significant and as such, SBR is the best concept option to recommend.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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APPENDIX A

Table A1. Ranking of concept options applying the relative weighting of the major criteria

Major criteria	Relative sub-criteria weight	Parameter weighting	CMAS	SBR	UASB
Environmental/ social impact (73%)	Effluent quality$^{\pm}$	35.04	5.9568	13.6656	15.4176
	Reduced odour production$^{\pm}$	5.11	0.3066	1.7374	3.0149
	Reduced amount of sludge yield$^{\pm}$	14.6	1.752	8.176	3.212
	Reduced required land area (foot print)	6.57	0.5256	2.4309	3.6135
	Usefulness of by-product	5.84	1.6425	1.6425	3.285
	Local availability of resources	5.84	3.796	1.3432	0.7008
Operability (5%)	Reduced number of reactors/units	1.35	0.135	0.3105	0.9045
	Reduced energy requirement	1.05	0.0945	0.2835	0.672
	Reduced sludge dislodging rate/interval	1.4	0.084	0.826	0.476
	Flexibility/ruggedness (adaptability to	0.4	0.048	0.244	0.108
	shock) $^{\pm}$	0.35	0.035	0.189	0.126
	Equipment reliability$^{\pm}$	0.45	0.036	0.2835	0.1305
	Ease of operation/maintenance/minimal human intervention$^{\pm}$				
Economic (12%)	Reduced operating/maintenance cost$^{\pm}$	9	0.72	5.22	3.06
	Increase capital cost	3	2.19	0.24	0.57
Schedule (10%)	Schedule for proposed execution$^{\pm}$	2.5	0.3	1.4	0.8
	Portability$^{\pm}$	5	0.45	3.2	1.35
	Constructability$^{\pm}$	2.5	1.825	0.475	0.2
	Total (Ranking)	100	20 (3)*	42 (1)	38 (2)

$^{\pm}$These are the boundary conditions with respect to the 4 major criteria
*20 (3) implies total score of 20 which ranks 3rd out of 3 concept options

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