ASSESSING THE SUSTAINABILITY OF WASTEWATER TREATMENT TECHNOLOGIES IN THE PETROCHEMICAL INDUSTRY[#]

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ABSTRACT

Selecting the most suitable industrial wastewater treatment technology is not only about providing the best technical solution at the lowest cost: it is also about sustainability (including social and environmental acceptance) and institutional feasibility. This paper demonstrates and evaluates a method that may be used for wastewater treatment technology assessment and selection in an industrial context, with a specific focus on biological wastewater treatment in a petrochemical company. The technology assessment objectives are formulated as complexity, generality, approach, lead-time and resources, focus, and data used. These objectives are used as criteria for the development of a technology assessment method: a multi-criteria decision analysis technique to compare and rank the wastewater treatment technology alternatives against the identified technical, socio-economic, and environmental objectives. Using a petrochemical operation in South Africa as a case study, the paper provides a systematic analysis of eight wastewater treatment alternatives to test the proposed technology assessment method, and thus determine its usefulness as a technology assessment technique. The investigation suggests that the method managed to achieve most of the technology assessment objectives of the organisation. Accordingly, suggestions for further development of the technology assessment technique are made.

OPSOMMING

Die keuse van die mees geskikte industriële afvalwater behandelingstegnologie handel nie net oor die verskaffing van die beste tegniese oplossing teen die laagste koste nie, maar ook oor volhoubaarheid (aanvaarding uit sosiale en omgewingsgeregtigheid standpunte) en institusionele haalbaarheid. Hierdie artikel demonstreer en evalueer 'n metode wat vir die seleksie en evaluering van afvalwater behandelingstegnologie gebruik kan word in 'n industriële konteks met 'n spesifieke fokus op die biologiese afvalwaterbehandeling in 'n petrochemiese maatskappy. Die tegnologie-assesseringsdoelwitte is geformuleer as kompleksiteit, algemeenheid, benadering, aanlooptyd en hulpbronne, fokus, en data gebruik. Hierdie doelwitte word gebruik as kriteria vir die ontwikkeling van 'n tegnologie assesseringsmetode; 'n multi-kriteria besluit analise tegniek om die afvalwater behandeling tegnologie alternatiewe te vergelyk en te rangskik teen die geïdentifiseerde tegniese, sosio-ekonomiese, en omgewingsfaktore doelwitte. Deur die gebruik van 'n petrochemiese bedryf in Suid-Afrika as 'n gevallestudie, bied die artikel 'n sistematiese ontleding van agt afvalwater behandeling alternatiewe om die voorgestelde tegnologie assesseringsmetode te toets en die nut daarvan dus te bepaal as 'n tegnologie assessering tegniek. Die ondersoek dui daarop dat die metode daarin slaag om die meeste van die tegnologie-assesserings-doelwitte van die organisasie te bereik. Voorstelle vir verdere ontwikkeling van die tegnologie assessering tegniek word dienooreenkomstig gemaak.

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1. INTRODUCTION

Water is recognised internationally as an important resource, and the optimisation and reuse of water is increasingly prioritised, particularly in water-scarce countries such as South Africa. Various technologies have been developed for the biological treatment of water. Traditionally, activated sludge and trickling filters have been considered the industry standard for the biological treatment of organically contaminated water. This is currently the case for large petrochemical operations in South Africa.

At one such facility, the current process scheme has ten aerobic-activated sludge basins that treat a mixture of the following process waters: oil-contaminated water from factory rundown; by-product water from the synthesis process; and by-product water from the coal gasification process.

The water streams are treated in an activated sludge process and re-used as process cooling water make-up. Micro-organisms break down the organic materials within the process waters. The micro-organisms are contained in a variety of aerobic digesters that require oxygen to biodegrade the organic compounds. To provide the required oxygen, air is supplied via blowers and introduced via an aeration grid in the basin.

1.1 The water treatment problem in the operation

The organisation is in the process of expanding its operations both nationally and internationally. In line with global standards, all new operational designs employ total re-use or zero liquid-effluent discharge approaches. This has the dual benefit of reducing water demand (through recycling) and avoiding off-site impacts on the surrounding environment. Parallel technology assessments now aim at expanding existing water treatment capacity and retrofit options, as well as investigating green field developments.

With this specific operation in the organisation, the current activated sludge treatment facility is overloaded hydraulically and with contaminant load, resulting overall in the deteriorating quality of the process cooling water make-up. This, in turn, leads to increased fouling and/or scaling of heat exchangers, ultimately impacting on final product production. The problem is further exacerbated by the unique characteristics of the effluent steams; thus case studies and best practices in related industries cannot be applied directly.

1.2 Objective of this study

Within the organisation it has been identified that, with the large number of capital projects, technology offerings, and limited resource availability, making project decisions (while still meeting budget and schedule demands) becomes a challenging process. A preliminary investigation identified the need for a specific method to establish criteria and assessment boundaries to screen technologies for unique applications. The associated research questions, within the context of the specific organisation, were as follows:

- What are the factors governing the selection of appropriate technologies within the petrochemical industry, and in this organisation in particular?
- Which units of measurement and scales for evaluation would be appropriate for each indicator?
- Is the developed model adequate for the evaluation of water treatment technologies within the industry?

The objective was then to develop and evaluate a technology assessment method that could be used to screen wastewater treatment technologies within the organisation.

2. CONCEPTUAL METHOD

Meerholz [1] provides: a detailed literature analysis of the history and development of technology selection; various commonly-used technology assessment techniques; available biological wastewater treatment technologies; and technology assessment techniques used specifically for the selection of wastewater treatment technology.

From the literature review it is clear that technology assessment is an intensive task that requires significant time, involvement, and resources to generate the required results. Azzone & Manzini [2] also concluded that there is no single technology assessment method, and that the input into, and method of, technology assessment is dependent on the conditions and needs of the local environment. This is supported by the comprehensive overview of Tran & Diam [3] of the various available methods and tools for both public and private sectors. They concluded that technology assessment consists of a non-integrated number of tools and methods that can be applied in combination or independently, according to the application and the objective of the study. They also observed that no single tool could be applied to analyse the benefits of a new technology holistically. Some critics, such as Palm [4], have also pointed out that the quality of the outcome is usually proportionate to the financial means available.

For water treatment technology, a body of literature lists important factors to consider when evaluating and selecting such technologies. However, these are mostly focused on the needs of developed countries, with a specific focus on sanitary waste applications. Limited applications are found within industrial – particularly refinery or petrochemical – applications. From the available literature, emphasis is also placed on the technical aspects and cost of the technology, with little focus on economic, social, or institutional factors.

Despite this, it is clear from the literature review that:

- An assessment method must be able to handle quantitative and qualitative variables; and
- The characteristics of the relevant operational site must be incorporated into the selection method.

Singhirunnusorn & Stenstrom [5] provide a complete scope of the factors to be considered when conducting technology assessments in wastewater applications, although these are specific to the urban environment in developed countries. The categories are general in nature, and can be applied to the industrial environment – although the identified criteria and indicators must be adapted to specific needs, as no single set of criteria and indicators can be applied universally. The intent is thus to use the technical, socio-economic, and environmental factors as a guideline, and to apply these in the context of the specific organisation.

In general, from the literature review of Meerholz [1], the multi-criteria decision analysis (MCDA) method has proven to be popular in such applications, as seen from Jeffrey et al. [6] and Singhirunnusorn & Stenstrom [5]. This is because the method can be used for complex decisions where there are trade-offs between competing objectives.

The MCDA methods provide subjective and implicit decision-making that can be made objective and transparent in an evaluation model. Either quantitative or qualitative data can be considered in the same model.

An additive value function is used to aggregate component values. The overall value of an alternative x is evaluated as:

$$v(x) = \sum_{i=1}^{n} w_i v_i(x_i) \tag{1}$$

where: x_i = the consequence of an alternative x for attribute (criterion) i;
v_i *(x)* = the rating of an alternative x with respect to an attribute (criterion) i;
n = the number of attributes (criteria);
i = the attribute (criterion) of interest, i = 1, …, n; and
w_i = the relative importance of an attribute (criterion) i, $w_i > 0$.

Singhirunnusorn & Stenstrom [5] developed a comprehensive set of criteria and indicators for wastewater treatment selection, reflected in Figure 1.

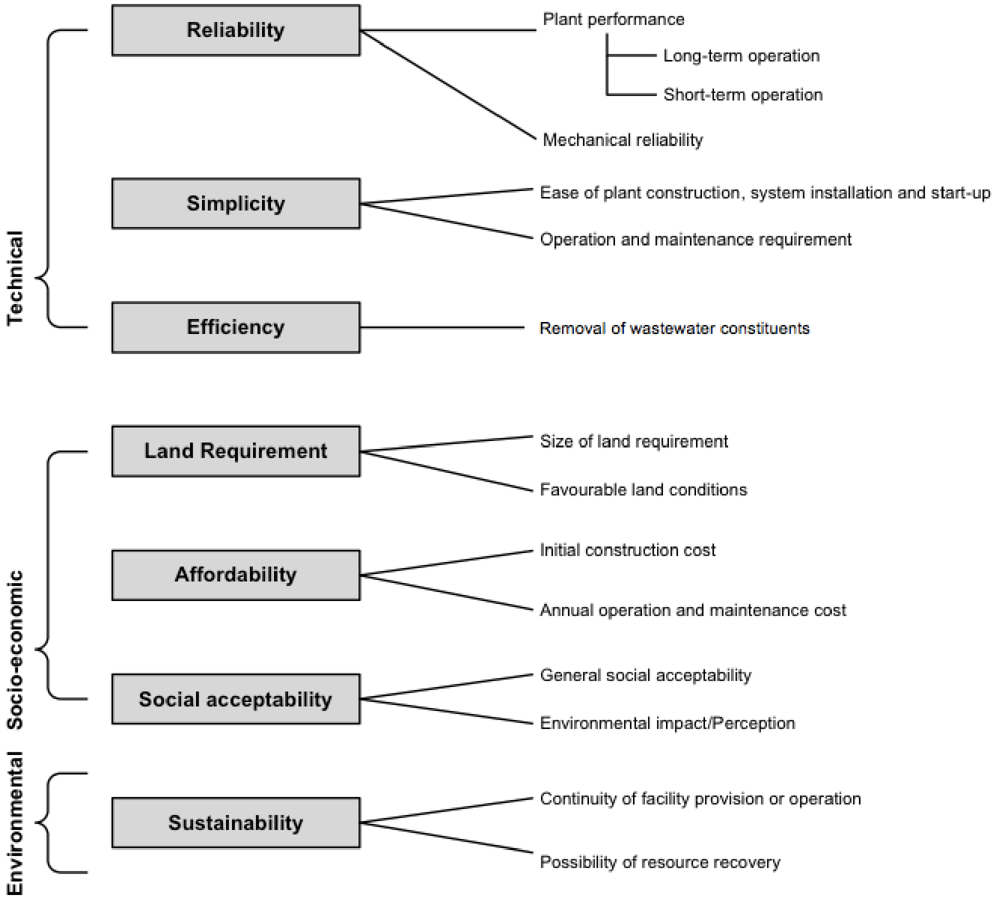

Figure 1: Factors determining the selection of appropriate wastewater treatment systems for developing countries

To ensure that a method is developed that satisfies the organisation's particular needs, the technology assessment method is required to meet certain criteria. These are discussed as a framework of assessment objectives.

3. FRAMEWORK OF ASSESSMENT OBJECTIVES

3.1 Complexity

It is a requirement that it should be possible to do the assessment during no more than two workshops, using supplier information, expert judgment from research and development personnel and available literature. In other words, readily-available sources of information can be used.

3.2 Generality

The principles used in the method have to be general in nature and, depending on the type of technology to be assessed, the indicators have to be adaptable to the specific application. In particular, for the specific organisation, it is required that the method be adaptable to brown field developments.

3.3 Approach, lead-time and resources

The method must require no more than two workshops.

3.4 Focus

The method has to facilitate focused discussions and assist the workshop participants constructively to discuss possible impacts of the various technologies.

3.5 Data used

The objective of the technology assessment is to determine the possible impact of the technology on the selected principles. It is anticipated that a blend of qualitative and quantitative data would be used, which would be sourced from expert opinion, available literature, and supplier information.

Apart from the technical aspects during the selection of wastewater treatment selection, a number of social, economic, institutional, and environmental concerns must be considered. By adapting the criteria and indicators identified by Singhirunnusorn & Stenstrom [5], a multi-criteria decision analysis (MCDA) technique was developed for specific application in this organisation.

With the framework of the new assessment technique defined, its usefulness needs to be determined. The key factors to be considered when assessing the performance of the proposed method are:

- The required information (for the indicators) must be readily available with limited cost implications, since assessing the projects must be time efficient.
- Appropriate project selection criteria must be representative of the aims and goals of the organisation's strategic objectives.
- Associated indicators defined must reflect the priorities of stakeholders.
- The developed selection criteria must be based on good project management practices, and must evaluate projects on economic viability, and environmental, social, and institutional performance.

The MCDA approach was chosen to meet the main objectives, as it has proven useful in problems where the different objectives and criteria are in conflict, and where both qualitative and quantitative data are required to conduct the mathematical and scientific analyses to support decision-making [7]. The data is mostly based on actual calculations, measurements of indices, results, or expert judgment.

4. RESEARCH METHODOLOGY

The proposed method was tested using an existing case study. A petrochemical facility in South Africa is in the process of investigating both integrated fixed film activated sludge (IFAS), and fixed and mixed media technology, as potential retrofitting or upgrading options to address the organic overloading problem and improve the process efficiency and robustness at the operation's water recovery plant. An overview of the proposed research design is provided in Figure 2.

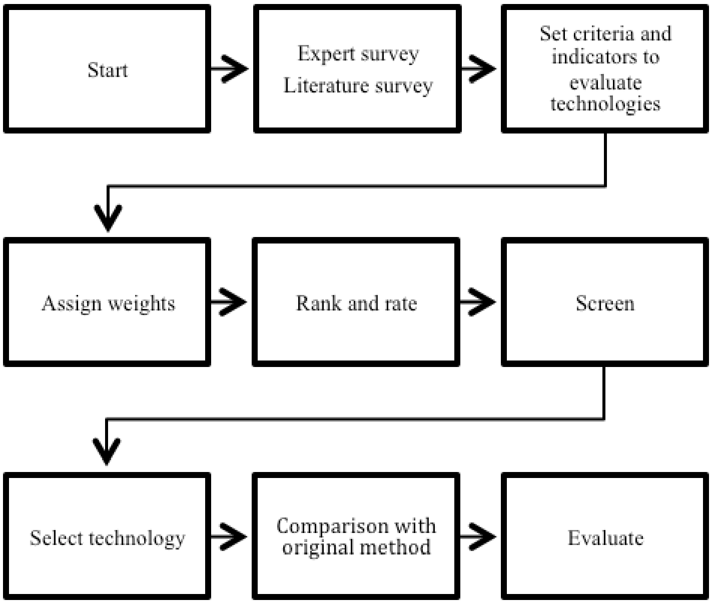

Figure 2: Overview of research design

To test the method, the case study approach was used on an existing water treatment problem within the facility. The problem to be investigated was the possible upgrading or expansion of the existing water recovery units to increase both the organic and the hydraulic treatment capacity. The project was already in the feasibility stage, and a technology selection had been conducted. The method was thus evaluated and compared with the current technology selection practices.

An initial workshop was held with a selected focus group to agree on proposed factors, criteria, and indicators. Any benchmarks or qualifying criteria were discussed, as well as the weighting assigned to each criterion.

The case study was conducted during a workshop using a focus group technique [8]. Interested and affected parties were invited to attend and participate. The objective of the workshop was to ensure a wide representation of all disciplines with specialist knowledge and experience within each of the factors under consideration.

The basic elements of the study consisted of the conceptual framework and the objectives of the method presented earlier.

5. RESULTS

The case study carried out a systematic analysis of eight possible treatment alternatives. An MCDA model was constructed from the criteria and indicators discussed in the previous section, according to the following steps:

Step 1: Determine the objective and assign weightings to the principles accordingly.
Step 2: Identify the technologies to be evaluated.
Step 3: Rate the alternative technologies with respect to each indicator.
Step 4: Rank-order the technologies.

5.1 Objective determination and weighting

A workshop was arranged to develop the final set of criteria and indicators, which was subsequently incorporated into the decision support model. Both objective and subjective approaches were used to create specific measures. (Refer to Table 1 for the indicators and criteria developed.) These are detailed further in Meerholz [1].

Table 1: The main objectives and weighting of each principle and criterion

Principle	Criterion	Objective
Efficiency weighting = 0,30	Removal of wastewater constituents	Determine the extent of constituent removal in the wastewater
Reliability weighting = 0,20	Long-term operation	Determine the variability of the technology performance and efficiency of treatment under normal and upset conditions
	Short-term operation	
	Mechanical reliability	Evaluate the probability of mechanical failures, and the impact of failures on effluent quality
Simplicity weighting = 0,18	Ease of plant construction, installation, and commissioning	Determine the ease with which construction materials can be sourced, compatibility with existing processes, level of automation
	Operation and maintenance requirements	Determine robustness of equipment, operational familiarity with the process, spares lead time
Sustainability weighting = 0,12	Continuity of system provision or operation	Determine ease with which system can be expanded, and whether technology has a life cycle of at least 25 years
	By-products	Determine which by-products or wastes are generated that require additional treatment
Affordability weighting = 0,10	Construction cost	Determine initial construction costs
	Overall annual operation and maintenance cost	Determine operational and maintenance expenses over the technology life cycle
Land requirement weighting = 0,08	Size of land requirement	Determine physical footprint of technology
	Favourable land conditions	Determine extent of site preparation required
Social acceptability weighting = 0,02	General social acceptability	Determine extent to which technology is accepted by the impacted community
	Perception of environmental impact	

5.2 Identify technologies

A number of processes were identified as possible alternatives ways to remove bottlenecks, in order to accommodate higher hydraulic and organic loads successfully. These were:

- Conventional activated sludge treatment;
- Membrane bio-reactor (MBR);
- Moving bed bio-reactor (MBBR);
- High-rate compact reactor (HCR);
- Retrofit MBBR;
- Up-flow packed bed biological aerated filter (BAF);
- Pure oxygen dosing (retrofit option); and
- Alternate aeration technology (retrofit option).

5.3 Rating and ranking

Rank ordering of the wastewater treatment alternatives was done per principle identified. For demonstration purposes, the results obtained for the simplicity principle are provided. This study considered the simplicity of the respective wastewater treatment technologies.

Simplicity of wastewater treatment in this framework refers to various aspects during the implementation, operation, and maintenance of the system. The indicators and variables selected to determine the reliability are presented in Table 2.

Table 2: List of selected indicators to evaluate simplicity

Indicator	Units	Description
Ease of plant construction, installation, and commissioning		
Complexity of plant construction	1 (very rare materials) to 5 (commonly available materials)	Determine extent to which rare materials are required for construction
Complexity of system installation	1 (very complex) to 5 (very low complexity)	Determine complexity of control system integration and philosophy
Complexity of system commissioning	1 (very rare materials) to 5 (commonly available materials)	General availability of start-up materials
Time required for construction	1 (very rare materials) to 5 (commonly available materials)	Determine equipment delivery lead times
Time required for system installation	1 (very complex) to 5 (very low complexity)	Determine number of control loops
Operation and maintenance requirements		
Complexity of operation and maintenance	1 (differs significantly from existing operations) to 5 (very similar to existing operations)	Determine robustness of equipment and operational familiarity with process
Skill and personnel requirement	1 (very low level of automation) to 5 (very high level of automation)	Determine level of process automation (extent of manual input required)
Specially manufactured or imported equipment and spare parts	1 (very rare materials) to 5 (commonly available materials)	Compare materials of construction and spares delivery lead time

The group assessed the technologies, and scores were assigned based on the team members' past experience or knowledge of each technology. The conventional activated sludge or alternate aeration technologies appeared to be most feasible where simplicity was the main objective.

The final results were compiled in a spread sheet. The average score was calculated per principle per technology and normalised to a value between 0 and 1, v_i (x). This value was then multiplied by the assigned weighting per principle, w_i. The results are shown in Figure 3.

From the analysis, the retrofit MBBR option achieved the highest score. The second alternative was the new MBBR option, with alternate aeration technologies and BAF coming in third and fourth respectively.

5.4 Sensitivity analysis

Should the objectives change with changing business requirements, a sensitivity analysis will be required to determine the extent to which the outcome of the analysis will change. For the sensitivity analysis, the weighting of one of the principles was assigned the maximum of 1, while the other principles were assigned a weighting of 0. This was done to determine the extent to which the assigned scores per technology influenced the eventual outcome. The results are shown in Table 3.

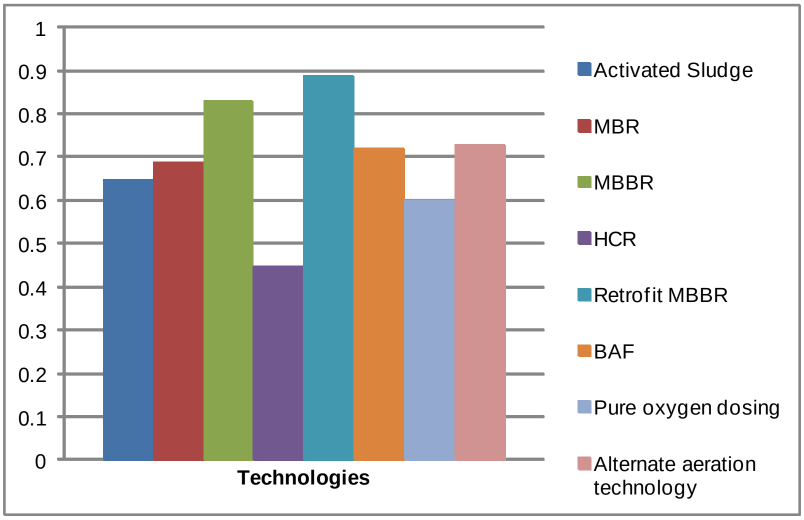

Figure 3: MCDA results for different wastewater treatment technologies

Table 3: Sensitivity analysis outcomes

Objectives	Technology
Maximum efficiency	MBBR and retrofit MBBR
Maximum reliability	Retrofit MBBR
Maximum simplicity	Activated sludge or alternate aeration technology
Maximum sustainability	Retrofit MBBR
Maximum affordability	Retrofit MBBR
Optimum land requirement	MBR or HCR
Maximum social acceptability	HCR

6. EVALUATION OF THE METHOD ACCORDING TO THE FRAMEWORK OF OBJECTIVES

On completion of the case study, the participants were asked to evaluate the method according to the framework of assessment objectives introduced earlier.

6.1 Complexity

It was a requirement that the assessment should be possible using supplier information, expert judgement from researchers in R&D, and available literature, in no more than two workshops. Readily-available sources of information could be used. The case indicated that the method was simple enough and that the various role players grasped the concept easily. The source of information proved to be slightly more complicated. When assessing the affordability of each technology, the extent of information required to conduct a meaningful analysis was underestimated. The company's internal commercial governance prevented the project team from sourcing the required information from vendors, and a dedicated cost estimator would have been required. The attendees at the workshop, however, agreed that they had enough knowledge to give an indication of what the relative costs would be, compared with the conventional activated sludge technology. This was deemed sufficient for the project phase, but all agreed that more detailed information and calculations would be required for subsequent project phases.

It was originally anticipated that more quantitative data would be used during the assessment. The extent to which each technology would be better than the others (for example, in social acceptability) was difficult to determine. During the discussions that were held, it was decided to score the technologies' expected performances relative to those of the conventional activated sludge treatment.

6.2 Generality

The principles used in the method are general in nature and, depending on the type of technology to be assessed, the indicators can be adapted to the specific application. The principles were easily adapted to the company's environment and to the project phase. In particular, it was required that the method be adaptable to brown field development. The case against which the method was tested entails the upgrading or expansion of an existing facility, and the indicators could be selected so that specific concerns – for example, integration with existing operations – are taken into consideration. Depending on the indicators selected, the assessment team agreed that the method could easily be adapted to a green field development.

6.3 Approach, lead-time, and resources

The nature of the selected indicators ensured that the method complied with the requirements set out above. The method did not require significant time to construct, which may be because the participants in the workshops were well-acquainted with the relevant technologies. It must be noted that, should the technology be compared with other alternatives, rating or ranking would prove problematic, since there is a limited value basis.

6.4 Focus

The method effectively highlighted the possible impact of the various technologies, and assisted the workshop participants in constructive discussions about this.

6.5 Data used

The objective of the technology assessment was to determine the possible impact of the technology on the selected principles. A blend of qualitative and quantitative data was used, sourced from expert opinion, available literature, and supplier information. The measures selected per indicator can be adapted to the extent of the information required or the development phase of the project. This makes the method an attractive option for use within the company.

6.6 Factors that influenced the study

The selected case that was used to evaluate the method passed the pre-feasibility stage during the course of this study. The project team had thus already made a technology selection based on efficiency alone; and they had already selected the retrofit MBBR option before the selection criteria could be determined. It was noticeable that there was a tendency among certain team members to 'push' the criteria towards those that would be favourable to the 'already selected' option. The team members had to be continually reminded that the objective was to compare the outcomes of the different approaches.

Although the role players involved had significant knowledge of the selected technologies, the information about the affordability of each technology was not based on actual figures or calculations. As mentioned before, this was due to an internal commercial governance issue that restricted the project team.

7. CONCLUSIONS AND RECOMMENDATIONS

For the selected weighting and scores assigned, the retrofit MBBR technology appears to be the most feasible technology to consider for demonstration-scale piloting. The least desired technology was the HCR option.

The sensitivity analysis indicates that the retrofit MBBR technology would remain the preferred option if the objectives were to change from achieving maximum efficiency to achieving maximum reliability, sustainability, or affordability. The preference for this technology would reduce if the objectives shifted towards achieving maximum simplicity, social acceptability, or optimum land use. The least desired technology, HCR, would become one of the more desired technologies should the objectives change towards social acceptability or optimum land use.

7.1 The future of the assessment method

The method was tested with a single case. Opportunities exist to test the method against more cases to determine whether any of the principles must be changed, or whether additional principles should be added. The project team did not feel it necessary to add or change any of the principles, although this may not be true for other cases.

One of the objectives was to ensure that the method would be able to accommodate both green and brown field developments. The example used was a brown field expansion. It is expected that other criteria, such as social acceptability and land use, would be some of the governing criteria in green field cases. A further test against a green field case should thus be conducted to determine the suitability of the model.

Given the conditions above, the following aspects of the method need to be refined and investigated further:

- The method must be applied on a real example during the project life cycle, and not retrospectively checking whether the initial selection was the correct one.
- The method must be applied to a green field case.
- The method must be applied to the evaluation of other water treatment technologies within the company.
- The method must be applied with full information available as originally envisaged – particularly the financial indicators.

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