A METHOD FOR SUSTAINABILITY EVALUATION OF SMALL WASTEWATER TREATMENT SYSTEMS

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ABSTRACT
The article presents the application of multi-criteria analysis for selection of the best treatment technology and the best technical solution of a small wastewater treatment plant. The calculations performed for two plant capacities and for various effluent standards are based on compromise programming method. The effluent standards considered for the smaller plant (133 PE) are only BOD_5, COD and TSS while for the larger plant (670 PE) also nitrogen and phosphorus. For each plant's capacity the three different treatment technologies are analyzed. The analyzed technologies included biofilters, continuous and cyclic activated sludge, rotating biological contactors and natural treatment methods. The selection of the best technology is done with a define set of sustainability criteria that can be easily modified and adjusted to specific local conditions. The proposed method can be used for selection of the best treatment technology and the technical solution at the stage of wastewater system planning and designing as well as for evaluation of already operated plants from sustainability standpoint.

KEYWORDS
small wastewater treatment plants, technology selection , multi-criteria analysis

INTRODUCTION

Operation of small wastewater treatment plants of capacity below 300 m^3/d (2000 PE) is different from operation of larger plants. This is mostly due to the increased variability in raw sewage flow and composition. Thus, the wastewater treatment technologies applied for small plants must easily adjust to varying conditions and to ensure required effluent quality. In addition it must be complemented with minimum required servicing and maintenance, and low operational costs. The decision regarding application of a specific technological solution at a small WWTP requires careful analysis of numerous technological and environmental issues, as well as the local conditions. Detail economic analysis is also necessary. Unfortunately, in practice such decision is often made only of the basis of low investment costs or it is a result of intensive marketing of a plants' vendors. In result often there are constructed small plants not properly suited to local wastewater quantitative and qualitative characteristics. Such plants are difficult to operate, unreliable, and they cannot guarantee sufficient treatment efficiency.

The participation of an experienced practitioner in the process of choosing the best technological solution for a small plant is very desirable. Such a person, supported with adequate analytical tools, can effectively assist in selection of the best technical solution considering specific local conditions. The analysis should include multi-criteria evaluation of technical, environmental, local and economic conditions. The article presents the specific example of application of multi-criteria analysis for selection of the best technology for two small wastewater treatment systems of different sizes.

TECHNOLOGIES USED AT SMALL WASTEWATER TREATMENT PLANTS

Legal regulations are essential in the process of selection of treatment technology at a small WWTP. In Poland the approved methods that can be used for wastewater treatment depend on wastewater quality and on the type of receiver where the effluent is discharged (*M.Env.Dir.of 24.07.2006 r.*). The domestic wastewater in amount not exceeding 5 m^3/d (33 PE) can be discharged to soil within the borders of the owner's property. This limitation strongly affects the choice of technologies that can be applied in the smallest, household plants. If the daily volume of wastewater exceeds 5 m^3/d it must be treated mechanically and biologically. Moreover, if the effluent is discharged to lakes and reservoirs also nitrogen and phosphorus must be removed.
The range of technologies that allow to meet the effluent requirements for a small WWTP comprises different types of biofilters, activated sludge (conventional, with extended aeration, or with nutrient removal), sand-gravel filtration, and natural methods that are used at hydrophyte plants. All these technologies are well known, tested and reliable. A diagram of various configurations for their application is presented in Fig. 1.

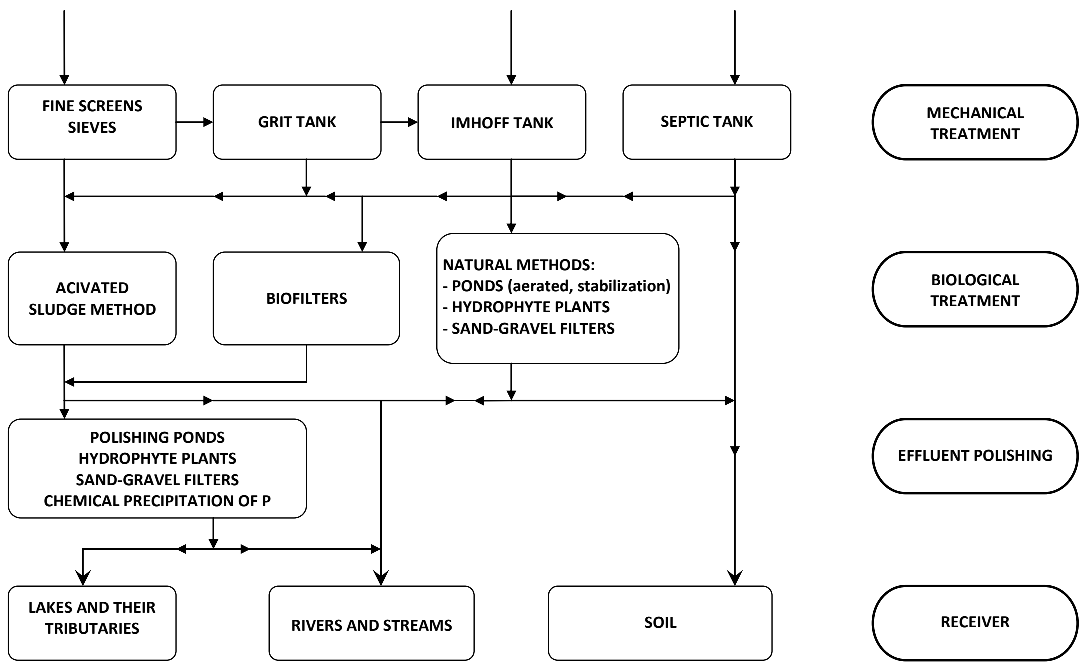

Figure 1. Processes and objects used for treatment of small volumes of wastewater

SUSTAINABILITY EVALUATION CRITERIA FOR SMALL WWTPs

The selection of the criteria that will be the basis for sustainability evaluation of technologies for small WWTPs is the starting point for multi-criteria analysis. There is no recommended set of criteria for such evaluation and different researchers use different criteria depending on specific characteristics of a sewage system, plant capacity, applied technologies, and the goal of the analysis (*Roeleveld, 1997; Lundin, 1999; Mucha, 2009*). Extended set of sustainability criteria that are used by different authors for evaluation of wastewater systems was presented by Balkema (*Balkema, 1998*). They were organized into several groups comprising economic, environmental, technical, and social and cultural factors. In the process of evaluation of small WWTPs as the most important should be considered widely understood environmental and aesthetic, technical and economic criteria as presented below:

Environmental criteria, that_refer directly to the Ministry of Environment's Directive regarding wastewater treatment and effluent quality (*M.Env.Dir.of 24.07.2006 r.*). This criteria is considered to be superior to all others as evaluated should be only those technologies that guarantee reaching the required effluent quality. In practice it may be assumed that all formally certified small WWTPs offered on the market fulfill this requirement, however some exceptions may exist. Other environmental criteria that should be considered in the analysis include odors, noise, nuisance associated with insects, and aesthetic appearance of the plant. The latter criterion may be especially important for the plants situated in a terrain of high environmental value (e.g. nature reserves) or close to historic places.

Technical criteria, that are important as it is expected that a small WWTP will be operated without continuous supervision. Thus, its technical design should be such that the plant's control should be very uncomplicated and it require only simple maintenance and servicing. In practice it translates into high level of automation of the plant's operation with the use of reliable and tested automatic control systems and the equipment. It should be noted here that a small WWTP is very sensitive to changing influent flow and composition, and under some conditions it may show the signs of failure even if all technical systems are operating correctly (e.g. toxic discharges, uncontrolled storm flows, etc.).

Economic criteria, that refer to both, capital and operational costs. For small WWTPs usually more attention is paid to capital costs that have to be paid in a short period of time. Operational costs are not so evident at the time when a specific technology and a technical design is selected. The cost structure for different technologies may vary significantly and sometimes may be decisive for the investment's success.

In the presented analysis the following set of specific sustainability evaluation criteria from the above described categories are used:

- ease of use, including maintenance time and frequency, and simplicity of the required works
- reliability of operation, including technical and technological reliability, and stability under changing conditions (temperature, sludge setting properties, shock-loading)
- economic aspects, including combined capital and operational costs calculated on annual basis, e.g. with use of Szelągowski formula (*Szelągowski, 1985*)
- environmental effects, including odors, noise, insects, etc.
- modernity of technical design, including monitoring and control systems, effective equipment, application of corrosion-resist materials
- aesthetics of the design, including integration with the landscape and overall appearance of the plant.

For the performed comparative multi-criteria analysis two plant capacities were used 20 m^3/d (133 PE) and 100 m^3/d (670 PE). Each plant size has different requirements regarding effluent quality - BOD_5, COD and TSS for the smaller plant, and BOD_5, COD, TSS, N and P for the larger one. For each plant's capacity analyzed were three technologies. The technologies considered for the smaller plant include:

- conventional activated sludge
- low-loaded biofilter
- hydrophyte plant with horizontal subsurface flow.

The larger plants use various compact mechanical and biological treatment with final chemical precipitation. In the biological stage analyzed were the following technologies:

- cyclic activated sludge (SBR)
- multi-stage activated sludge
- submerged aerated biofilter.

MULTI-CRITERIA ANALYSIS FOR SELECTION OF THE BEST TECHNOLOGY

Multi-criteria analysis is a mathematical method that can be used for selection of the best of the many considered options. The necessary condition for finding the solution is a set of well-designed criteria that can be used for evaluation of different options. The criteria taken into account should represent diverse goals that sometimes are even contradictory one to the other, e.g. a solution that is the cheapest and at the same time the most reliable. Thus the analyzed options should be defined in details and the final selection is always a compromise based on the relative weights assigned to individual criteria (*Statnikova et al. 2005; Brechet, 2009*).

Mathematical depiction of the decision problem is a decision matrix that includes description of specific options along with the considered evaluation criteria. The quantitatively presented criteria constitute the measure of fulfillment of the assumed objectives and goals that should be achieved with each specific option. The decision matrix is shown in Table 1. All the criteria are quantified in scale from 0 to 10, where 0 is the lowest and 10 is the highest mark.

Table 1. Decision matrix for selection of the best technology for the plant 20 m^3/d (133 PE)

Technology evaluation criteria	Evaluated technologies applied at small WWTPs		
	Activated sludge (conventional)	Biofilter (low-loaded)	Hydrophyte plant
Simplicity and ease of use	7	9	10
Reliability	7	8	10
Economy	8	9	10
Effects to environment	10	10	8
Modernity of design	9	10	7
Aesthetics	8	8	10

The decision task was solved with compromise programming method (*Aragonés-Beltrána et al., 2009*). It allows to organize the options in order from the worst to the best one using the concept of their arrangement according to the distance from so called "ideal point" with the coordinates $X'(x_1', x_2',...,x_m')$. All coordinates of the ideal point are equal to a maximum value of the assumed normalization scale, i.e. the point is always in the most advantageous position. Mathematical depiction of the searched distance of the analyzed option from an ideal point can be presented as follow (Eq. 1):

$$L_\alpha(s_n) = \sum_{m=1}^{M} w_m^\alpha \cdot (x_m' - r_{NM}')^\alpha \qquad \text{(Eq. 1)}$$

And the selection of the best option is done according to the following rule (Eq. 2):

$$s_j = \bar{s} \Leftrightarrow L_\alpha(s_j) = \min L_\alpha(s_n);\, n = 1, 2, ..., N \qquad \text{(Eq. 2)}$$

where:

- $L_\alpha(s_n)$ - measure of divergence of a specific option s_n from the ideal point
- š - selected option,
- w_m - weight coefficient for the criterion "m",
- x_m' - „m" coordinate of the ideal point,
- r_{NM}' - normalized value of a criterion,
- M - number of criteria,
- α - exponent that measures the divergence of a criteria from the ideal point X'; in practice equal to 1, 2 and ∞.

In the method the criteria that are more important for a decision-maker may be assigned a larger weight. In order to make the research more impartial and to track the results of the calculations the higher weight was assigned in sequence to each criterion. The hierarchy of criteria importance was based on results of surveys and the interviews with practitioners working with small WWTPs – operators, designers, merchandisers, constructors and scientists. The obtained results were quantified and became the basis for calculation of the weights.

Based on these sources of information it was found the most important criteria for evaluation of small WWTPs were: the simplicity and the ease of use (weight 0,25), reliability (weight 0,25) and economy (weight 0,2). The other criteria were not considered to be so important: effects to environment (weight 0,15), modernity of the design (weight 0,1) and the overall aesthetics (weight 0,05). The results of the calculations are shown in table 2. The abbreviated names of technologies are as follow: **AS -** activated sludge; **LLBio** – low-loaded biofilter; **Hyd** – hydrophyte plant.

Table 2. Ranking of the technologies used at small WWTPs 20 m^3/d (133 PE) according to the weights of individual criteria

Importance of criteria	Ranking of the technologies used at small WWTPs		
	α = 1	**α = 2**	**α = ∞**
1:1:1:1:1:1	Hyd*→LLBio→AS	LLBio*→Hyd→AS	Hyd*↔LLBio*↔AS*
2:1:1:1:1:1	Hyd*→LLBio→AS	LLBio*↔Hyd*→LLBio	Hyd*↔LLBio*↔AS*
5:1:1:1:1:1	Hyd*→LLBio→AS	Hyd*→LLBio→AS	Hyd*↔LLBio*↔AS*
1:2:1:1:1:1	Hyd*→LLBio→AS	Hyd*→LLBio→AS	Hyd*↔LLBio*↔AS*
1:5:1:1:1:1	Hyd*→LLBio→AS	Hyd*→LLBio→AS	Hyd*↔LLBio*↔AS*
1:1:2:1:1:1	Hyd*→LLBio→AS	LLBio*↔Hyd*→LLBio	Hyd*↔LLBio*↔AS*
1:1:5:1:1:1	Hyd*→LLBio→AS	Hyd*→LLBio→AS	Hyd*↔LLBio*↔AS*
1:1:1:2:1:1	LLBio*→Hyd→AS	LLBio*→Hyd→AS	Hyd*↔LLBio*↔AS*
1:1:1:5:1:1	LLBio*→AS→Hyd	LLBio*→AS→Hyd	Hyd*↔LLBio*↔AS*
1:1:1:1:2:1	LLBio*→Hyd→AS	LLBio*→AS→Hyd	Hyd*↔LLBio*↔AS*
1:1:1:1:5:1	LLBio*→AS→Hyd	LLBio*→AS→Hyd	Hyd*↔LLBio*↔AS*
1:1:1:1:1:2	Hyd*→LLBio→AS	Hyd*→LLBio→AS	Hyd*↔LLBio*↔AS*
1:1:1:1:1:5	Hyd*→LLBio→AS	Hyd*→LLBio→AS	Hyd*↔LLBio*↔AS*
5:5:1:1:5:5	Hyd*→LLBio→AS	LLBio*→Hyd*→AS	Hyd*↔LLBio*↔AS*
1:1:5:5:1:1	LLBio*→Hyd→AS	LLBio*→Hyd→AS	Hyd*↔LLBio*↔AS*
5:5:5:1:5:5	Hyd*→LLBio→AS	Hyd*→LLBio→AS	Hyd*↔LLBio*↔AS*
5:5:1:5:5:5	Hyd*→LLBio*→AS	LLBio*→Hyd→AS	Hyd*↔LLBio*↔AS*
5:5:4:3:2:1	Hyd*→LLBio→AS	Hyd*→LLBio→AS	Hyd*↔LLBio*↔AS*

* - acceptable options

The technologies shown inTable 2 are ranked in order from the most to the least preferred using sign „→" and considering the evaluation criteria presented in Table 1. The sign „↔" means that that the technologies are equivalent, i.e. equally distant from the ideal point. The importance of the specific evaluation criteria is presented in the first column in the table. For example, in the first row all considered criteria have the same weights (equal to1), while in the second row the first criterion ("simplicity and ease of use") has weight equal to 2 and all other criteria have weights equal to 1. This method allows for even more weighting of the criteria through varying the value of exponent "*α*". It can provide an extra weight to each divergence from the ideal point proportionally to its value. For high *α* values the large divergences of a specific technological option from the ideal point are more important. Three calculation examples for different *α* values are shown in Table 2. The decision-maker can assume certain limitations in selection of the best option. In this research the limitation was so called "acceptability level" and is calculated as shown in Eq. 3:

$$s_n^{*)} = 0{,}1 * L_\alpha (s_n)_{\min} \qquad \text{(Eq. 3)}$$

The acceptable technological options are marked with „*" in Table 2 and they constitute the solution of the decision task being an option that is located acceptable close to the ideal point.

The separate analysis was performed for the larger plant with the same compromise programming method and the same evaluation criteria as for the former case. The abbreviated names of technologies used in this analysis are as follow: **SBR** – sequencing batch reactor with activated sludge; **SABio** – submerged aerated biofilter; **MFAS** – multi-phase activated sludge. The decision matrix for this analysis is presented in Table 3 and the results of the analysis in Table 4.

Table 3. Decision matrix for selection of the best technology for the plant 100 m^3/d (670 PE)

Technology evaluation criteria	Evaluated technologies applied at small WWTPs		
	SBR	Submerged aerated biofilter	multi-phase AS
Simplicity and ease of use	10	9	8
Reliability	9	10	7
Economy	8	10	9
Effects to environment	10	10	9
Modernity of design	10	8	6
Aesthetics	10	9	7

Table 4. Ranking of the technologies used at small WWTPs 100 m^3/d (670 PE) according to the weights of individual criteria

Importance of criteria	**Ranking of the technologies used at small WWTPs**		
	α = 1	**α = 2**	**α = ∞**
1:1:1:1:1:1	SBR*→SABio→MFAS	SBR*→SABio→MFAS	SBR*↔SABio*↔MFAS*
2:1:1:1:1:1	SBR*→SABio→MFAS	SBR*→SABio→MFAS	SBR*↔SABio*↔MFAS*
5:1:1:1:1:1	SBR*→SABio→MFAS	SBR*→SABio→MFAS	SBR*↔SABio*↔MFAS*
1:2:1:1:1:1	SBR*↔SABio*→SBR	SABio*→SBR→MFAS	SBR*↔SABio*↔MFAS*
1:5:1:1:1:1	SABio*→SBR→MFAS	SABio*→SBR→MFAS	SBR*↔SABio*↔MFAS*
1:1:2:1:1:1	SABio*→SBR→MFAS	SABio*→SBR→MFAS	SBR*↔SABio*↔MFAS*
1:1:5:1:1:1	SABio*→SBR→MFAS	SABio*→MFAS→SBR	SBR*↔SABio*↔MFAS*
1:1:1:2:1:1	SBR*→SABio→MFAS	SBR*→SABio→MFAS	SBR*↔SABio*↔MFAS*
1:1:1:5:1:1	SBR*→SABio→MFAS	SBR*→SABio→MFAS	SBR*↔SABio*↔MFAS*
1:1:1:1:2:1	SBR*→SABio→MFAS	SBR*→SABio→MFAS	SBR*↔SABio*↔MFAS*
1:1:1:1:5:1	SBR*→SABio→MFAS	SBR*→SABio→MFAS	SBR*↔SABio*↔MFAS*
1:1:1:1:1:2	SBR*→SABio→MFAS	SBR*→SABio→MFAS	SBR*↔SABio*↔MFAS*
1:1:1:1:1:5	SBR*→SABio→MFAS	SBR*→SABio→MFAS	SBR*↔SABio*↔MFAS*
5:5:1:1:5:5	SBR*→SABio→MFAS	SBR*→SABio→MFAS	SBR*↔SABio*↔MFAS*
1:1:5:5:1:1	SABio*→SBR→MFAS	SABio*→MFAS→SBR	SBR*↔SABio*↔MFAS*
5:5:5:1:5:5	SBR*→SABio→MFAS	SBR*→SABio→MFAS	SBR*↔SABio*↔MFAS*
5:5:1:5:5:5	SBR*→SABio→MFAS	SBR*→SABio→MFAS	SBR*↔SABio*↔MFAS*
5:5:4:3:2:1	SABio*→SBR→MFAS	SABio*→SBR→MFAS	SBR*↔SABio*↔MFAS*

* - acceptable options

ANALYSIS OF THE RESULTS

The analysis for small plants (20 m^3/d, 133 PE) show that the obtained results should be examined in two groups, for α = 1 i 2 and for α = ∞. For α = 1 and 2 there were 36 calculations with different weights assigned to specific evaluation criteria. Among these results 21 times a hydrophyte plant and 15 times a low-loaded biofilter were selected as the best technologies. For α = ∞ all three technological options are equally distant form the ideal point (the calculated distance in equal to 0). One of the possible explanation of such results are very small differences between the marks of individual criteria (Table 1). Thus, according to these criteria the technologies are very similar one to the other. On the other hand in the analysis the activated sludge technology 26 times was indicated as the worst technological option. The last row in Table 2 show the results of calculation where the weights of individual criteria were set by a group of experts during the public consultations. These results confirm that according to the selected criteria the best technological option is a hydrophyte plant, and next a low-loaded biofilter. It can be concluded that for small WWTPs hydrophyte plants and low-loaded biofilters are equally good technological options. Low-loaded biofilter is a preferred option when larger weights are allocated to the criteria related to environmental effects and modernity of a technical solution.

The results of the multi-criteria analysis performed for larger plants (100 m^3/d, 670 PE) also should be examined in two groups, for $\alpha = 1$ i 2 and for $\alpha = \infty$. For $\alpha = 1$ and 2 there were 36 calculations with different weights assigned to specific evaluation criteria. Among these results 25 times the SBR and 11 times the submerged aerated biofilter were selected as the best technologies. For $\alpha = \infty$ all three technological options are equally distant form the ideal point (the calculated distance in equal to 0). One of the possible explanation of such results are very small differences between the marks of individual criteria (Table 1). Thus, according to these criteria the technologies are very similar one to the other. On the other hand in the analysis the activated sludge technology 26 times was indicated as the worst technological option. The multi-phase activated sludge technology 31 times was indicated as the worst technological option. The last row in Table 4 show the results of calculation where the weights of individual criteria were set by a group of experts during the public consultations. These results show that according to the selected criteria the best technological option is submerged aerated biofilter. It can be concluded that for WWTPs of this capacity the cyclic activated sludge technology (SBR) is the preferred option. Submerged aerated biofilter is a favored option when option when larger weights are allocated to the criteria related to plant's reliability and economical aspects.

CONCLUSIONS

The selection of a technology for small wastewater treatment plant in a specific location should be based on a multi-criteria analysis of various acceptable options. Only the technologies that meet the legal requirements regarding effluent quality should be considered. At the plants of capacities below 1,000 PE and with no requirements regarding nutrient removal biofilters usually are the preferred options due to its operational simplicity and low energy demand. As an alternative solution hydrophyte plants can be considered, however with some limitations resulting from large area demand. For the plants of larger capacities and in situations when nutrient removal is required, the cyclic activated sludge systems (SBR) should be applied.

The method presented in this paper can be useful in selection of the best treatment technology and the technical solution at the stage of wastewater system planning and designing as well as for evaluation of already operated plants from sustainability standpoint. It can protect the investor from spending the money on the plants that do not guarantee achieving expected technological effects or can create significant operational problems.

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