

Hierarchical Decision Approach: Key to Activated Sludge Process Redesign

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Abstract

Hierarchical Decision Process has been applied to redesign a wastewater treatment plant to achieve phosphorus removal. The Hierarchical Decision Process suggests the order in which the decisions should be taken during the development of the new process, starting with the design of the reactor due to the strong interaction with the rest of the process. The redesign task is formulated as a multicriteria problem and considers simultaneously environmental, economical, legal and technical aspects. Finally, a sensitivity analysis is made to test the robustness and support the decision making procedure.

Keywords: Activated sludge, Conceptual design, Nutrient removal, Hierarchical decision process, Multicriteria analysis.

1. Introduction

The application of the European Directive (91/271/EEC) for urban wastewater treatment in sensitive areas requires a higher efficiency in nutrient removal from activated sludge plants. To achieve the strict phosphorus and nitrogen discharge limits implies a redesign of several units. Literature describes different options to enhance activated sludge performance and efficiency (Metcalf and Eddy, 2003), which have to be evaluated and compared at the early redesign stage. One of the options is the use of Conceptual Design, which involves a sequence of decisions (issues) about technologies, equipment, dimensions, configuration and operating conditions to develop a process. Conceptual design problems are complex and ill-defined because there are a large number of potential solutions to consider for a certain decision. To reduce the solution space, Hierarchical Decision Process (HDP) was proposed (Douglas, 1988; Smith, 1995). This approach breaks down the conceptual design into several tasks providing an easier way to analyse and evaluate them. Thus, the design process starts with the resolution of all the issues related to the core section of the plant (reactor) and then the design procedure is moved outward by adding the separation and the recirculation sections until a comprehensive design of the plant is achieved.

The aim of this paper is to show the benefits of applying the HDP in the redesign of a BNR plant (Biological Nitrogen Removal) to achieve phosphorus removal. The problem of the evaluation procedure is solved applying a multi-criteria method (Flores et al., 2004).

2. Methodology

This section describes the application of the HDP in the re-design of activated sludge plants. The HDP fixes the order of all the issues that arise in the redesign process (following the “onion logic” starting the design solving all the issues related to the reactor section). For each issue, a finite set of options that represent the alternative scenarios are generated [$A = \{A_1, \dots, A_m\}$]. Different criteria [$X = \{X_1, \dots, X_n\}$] are used to measure the accomplishment of re-design objectives [$OBJ = \{OBJ_1, \dots, OBJ_z\}$]. Weighting factors are assigned to determine the relative importance of the objectives [$w_i, i = 1, \dots, z$]. Weights are normalized to sum to 1 [$\sum w_i = 1$].

All the criteria used [X] are quantified by dynamic simulation, cost estimation and expert knowledge. The quantification of option A_j on criteria X_i is indicated with x_{ij} . Thus, each option under evaluation can be seen as a vector of scores and it can be represented as a n-dimensional performance score profile: [$A_j = (x_{1n}, \dots, x_{nj})$].

Value functions [$v(X_i)$] map the score profiles of all options [$v(A_j) = v(x_{1n}, \dots, x_{nj})$] into a normalized value from 0 to 1. The 0 and 1 values are associated with the worst (x_{i*}) and the best (x_i^*) situation whilst a mathematical function is used to evaluate the intermediate effects. The collection of the best [$x^* = (x_1^*, \dots, x_n^*)$] and the worst [$x_* = (x_{1*}, \dots, x_{n*})$] scores for all criteria determine the best [$v(x^*) = v(x_1^*, \dots, x_n^*) = 1$] and the worst profiles [$v(x_*) = v(x_{1*}, \dots, x_{n*}) = 0$].

With the grey scale evaluation (Copp, 2003), for every criterion (X_i) shades from 0 % to 100 % black are associated with the best (x_i^*) and the worst (x_{i*}) criteria values respectively. Grey intensity of the other options is determined by linear interpolation between these values.

Finally, a weighted sum (see eq. 1) is made to obtain a single value for each option. The weighted sum is calculated by adding the product of each normalized criterion $v(x_{ij})$ by its corresponding weight (w_i). The options are ranked according to the score obtained.

$$v(A_j) = v(x_{1j}, \dots, x_{nj}) = \sum_{i=1}^n w_i \cdot v(x_{ij}) \quad (1)$$

The option with the highest score is the recommended, but the final decision rests on the designer, mainly in those cases where the relative differences between the different options is not significant.

The design starts at the reactor because it is the most important section of the whole process. It is important to note that the reactor design dictates some of the basic decisions referred to the separation and the recycle. Once all the issues related to the reactor section are evaluated, the process re-design is moved outward evaluating the subsequent layers related to the separation and recycle section

3. Case-Study

3.1 Redesign procedure

The HDP methodology is applied to redesign the benchmark denitrifying plant (Copp, 2003) to achieve simultaneous carbon, nitrogen and phosphorus removal. The benchmark plant is a modified Ludzack Ettinger configuration with five reactors in series (tanks 1 and 2 are anoxic with a total volume of 2000 m³, while tanks 3, 4 and 5 are aerobic with a total volume of 3999 m³) linked with an internal recirculation from the 3rd aerobic tank to the 1st anoxic tank, a 10-layer secondary settling tank (with a total volume of 6000 m³) and two PI control loops. The first loop controls the dissolved oxygen in the 3rd aerobic tank by the manipulation of the aeration flow, and the second loop controls the nitrate level in the 2nd anoxic tank by manipulating the internal recycle flowrate.

The removal of phosphorus from wastewater involves the incorporation of phosphate into the total suspended solids and the subsequent removal of these solids. Phosphorus can be incorporated in to either biological solids (microorganisms) or chemical precipitates. The first issue in the hierarchy of decisions is related to the type of phosphorus removal in the reactor section. Three options are evaluated: (A₁) biological phosphorus removal, considering a preliminary 1250 m³ anaerobic tank (hydraulic residence time of 1.6 hours); (A₂) chemical phosphorus precipitation with iron salts in the 3rd aerobic reactor, with a constant dosage of 0.75 m³·day⁻¹ (750 kg·day⁻¹), and (A₃) hybrid solution with partial biological phosphorus removal (a 750 m³ preliminary anaerobic tank) enhanced with chemical precipitation in the 3rd aerobic reactor (constant dosage of 0.75 m³·day⁻¹).

Re-design objectives are: maximize effluent quality (OBJ₁); minimize effluent quality violations (OBJ₂); minimize construction and operational costs (OBJ₃) and maximize control performance (OBJ₄). In this case study we assume equal importance for all the re-design objectives, and thus $w_i = 0.25$ ($i = 1$ to 4).

A set of criteria is proposed to measure the achievement of these objectives. To measure the accomplishment of OBJ₁ one single criterion is proposed (X₁). This criterion is defined as the reduction percentage of the wastewater contaminant load entering the plant (eq 2). X₁ relates the effluent (EQ) to the influent (IQ) quality index (See Gernaey et al., 2004 for details about IQ and EQ quantification).

$$X_1 = \frac{IQ - EQ}{IQ} \cdot 100 \quad (2)$$

The effluent quality violation criteria (X₂, X₃, X₄, X₅ and X₆) are used to measure the accomplishment of OBJ₂ and reflect the percentage of time that the effluent concentration of the pollutant exceeds the effluent quality limits (91/271/EEC) during the evaluation period (1 week). The limits for these calculations were: C_{P-tot} = 2 g·m⁻³ (X₂); C_{N-tot} = 15 g·m⁻³ (X₃); C_{BOD} = 25 g·m⁻³ (X₄), C_{COD} = 125 g·m⁻³ (X₅) and C_{TSS} = 35 g·m⁻³ (X₆).

There are two criteria to measure the accomplishment of OBJ₃, both related to the minimization of the costs: X₇ (construction costs) and X₈ (operation and maintenance costs). $x_{7,1}$ is estimated based on the algorithms to design and evaluate wastewater treatment plants (Hydromantis, 2004b), $x_{7,2}$ is retrieved from expert knowledge and $x_{7,3}$

is a combination of both. X_8 is calculated according to the operating cost performance index (Vanrolleghem and Gillot, 2002), as stated by eq. 3.

$$X_8 = \alpha_{EQ} \cdot EQ + \alpha_{AE} \cdot AE + \alpha_{PE} \cdot PE + \alpha_{sldg} \cdot P_{sldg} + \alpha_{ME} \cdot ME + \alpha_{FE} \cdot FE \quad (3)$$

EQ is the effluent quality index; AE, PE and ME represents the aeration, pumping and mixing energy rates ($\text{kW} \cdot \text{h} \cdot \text{day}^{-1}$), respectively. P_{sldg} is the sludge production rate ($\text{kg} \cdot \text{day}^{-1}$) and FE is the quantity of chemicals ($\text{m}^3 \cdot \text{day}^{-1}$). The equations to calculate AE, PE, ME and P_{sldg} can be found in Copp 2003. FE is calculated integrating the quantity of iron salts during the evaluation period. The α_j coefficients in eq3 are the operating costs weighting factors and represent yearly operating costs. The values used in the simulations reported in this paper are: $\alpha_{EQ} = 50(\text{€} \cdot \text{year}^{-1}) \cdot \text{EQ}^{-1}$; $\alpha_{AE} = \alpha_{PE} = \alpha_{ME} = 25(\text{€} \cdot \text{year}^{-1}) \cdot (\text{kW} \cdot \text{h} \cdot \text{day}^{-1})^{-1}$; $\alpha_{sldg} = 75(\text{€} \cdot \text{year}^{-1}) \cdot (\text{kgTSS} \cdot \text{day}^{-1})^{-1}$ and $\alpha_{FE} = 190(\text{€} \cdot \text{year}^{-1}) \cdot (\text{m}^3 \text{Fe(OH)}_3 \cdot \text{day}^{-1})^{-1}$. All the α_j values are obtained from literature (Vanrolleghem and Gillot, 2002), but α_{FE} that is estimated

For OBJ_4 a control performance index, measured with the ISE (Integral Squared Error) is used. The controlled variable is the nitrate concentration in the 2nd anoxic tank (Z_{OBSERVED}), and the deviation from the setpoint ($Z_{\text{SETPOINT}} = 1 \text{ g N-NO}_3 \cdot \text{m}^{-3}$) during the evaluation time ($t_F - t_0$) is integrated to obtain X_9 . This index is represented in eq. 4.

$$X_9 = \int_{t_0}^{t_F} e^2 dt = \int_{t_0}^{t_F} (Z_{\text{SETPOINT}} - Z_{\text{OBSERVED}})^2 dt \quad (4)$$

Criteria X_1 , X_2 , X_3 , X_4 , X_5 , X_6 , X_8 and X_9 are quantified by dynamic simulation with the commercial software GPS-X (Hydromantis 2004a). The IWA's Activated Sludge Model# 2d was chosen as the biological process model (Henze et al. 1999) and the double-exponential settling velocity function of Takács et al. (1991) was chosen as a fair representation of the settling process. Default values at 15°C for kinetic and stoichiometric parameters are used for the simulations except for phosphorus precipitation kinetics that were adjusted (Gernaey et al., 2002). CAPDETworks (Hydromantis 2004b) software package provides the information for $x_{7,1}$ and partially for, $x_{7,3}$

Once the criteria are quantified we obtain the score profile for each evaluation option. Thus for the option A_1 its score profile is $A_1 = (75.59, 100, 87.92; 0, 0, 0, 67 \cdot 10^4, 1.01 \cdot 10^5, 1.08)$, for the option A_2 its score profile is $A_2 = (79.04, 69.84, 100, 0, 0, 0, 3000, 9.50 \cdot 10^5, 1.42)$ and finally for A_3 its score profile is $A_3 = (80.94; 72.71, 97.92, 0, 0, 0, 42 \cdot 10^4, 9.24 \cdot 10^5, 0.85)$.

The extreme profiles (based on expert judgement) for the criteria used in this case study are: $v(x)^* = (x_1 = 100, x_2 = 0, x_3 = 0, x_4 = 0, x_5 = 0, x_6 = 0, x_7 = 0; x_8 = 7.00 \cdot 10^5; x_9 = 0) = v(x_1^*, \dots, x_9^*) = 1$ and $v(x)^* = (x_1 = 0, x_2 = 100, x_3 = 100, x_4 = 100, x_5 = 100, x_6 = 100; x_7 = 1.00 \cdot 10^6, x_8 = 1.00 \cdot 10^6, x_9 = 1.5) = v(x_1^*, \dots, x_9^*) = 0$. Then a linear model between these extreme values is adjusted to calculate the intermediate effects. (for criterion X_1 has the following value function $v(X_1) = 0.01 \cdot X_1$).

With the grey scale evaluation (Table 1) we can observe that A_1 is the option that achieves the highest percentage of nitrogen removal (see the normalized value $v(x_{3,1})$ of $x_{3,1}$) but this fact is poorly reflected in the final decision. On the other hand A_2 has the lowest construction costs (see $v(x_{7,2})$) and the highest percentage of phosphorus

removal (see in $v(x_{2,2})$). A_3 gets the better values of effluent quality, control performance and operational costs as can be seen in $v(x_{1,3})$, $v(x_{8,1})$ and $v(x_{9,1})$ being A_3 the option that better achieves objectives 1 (OBJ₁) and 4 (OBJ₄). Note that for this case study, criteria X_4 , X_5 and X_6 are not useful to discriminate the alternative designs.

Table 1. Normalized criteria, grey scale evaluation and weighted sums.

OBJ _z	$v(x_{i,j})$	A_1	A_2	A_3	w_i
OBJ ₁	$v(x_{1,j})$	0.76	0.79	0.81	0.25
	$v(x_{2,j})$	0.00	0.30	0.27	0.05
	$v(x_{3,j})$	0.12	0.00	0.02	0.05
OBJ ₂	$v(x_{4,j})$	1.00	1.00	1.00	0.05
	$v(x_{5,j})$	1.00	1.00	1.00	0.05
	$v(x_{6,j})$	1.00	1.00	1.00	0.05
OBJ ₃	$v(x_{7,j})$	0.33	1.00	0.58	0.125
	$v(x_{8,j})$	0.00	0.17	0.26	0.125
OBJ ₄	$v(x_{9,j})$	0.28	0.05	0.43	0.25
$\sum_{i=1}^n w_i \cdot v(x_{ij})$		0.46	0.52	0.58	1.00

Thus, according to the re-design objectives defined, A_1 and A_2 are rejected, being A_3 the selected option. Nevertheless, in order to test the robustness of the decision a weight sensitivity analysis is made.

3.2 Sensitivity Analysis

The weight sensitivity analysis is made between OBJ₁, OBJ₂ and OBJ₃. The weight for OBJ₄ rests constant ($w_4 = 0.25$), while the remaining 0.75 (as mentioned above, the sum of all the weights has to be 1) is distributed between the weights of OBJ₁ (w_1), OBJ₂ (w_2) and OBJ₃ (w_3). The weighted sum for the three competing options is recalculated to obtain a rank of the final scores. The same procedure is applied for a second sensitivity analysis but in this case the analysis is made between w_2 , w_3 and w_4 .

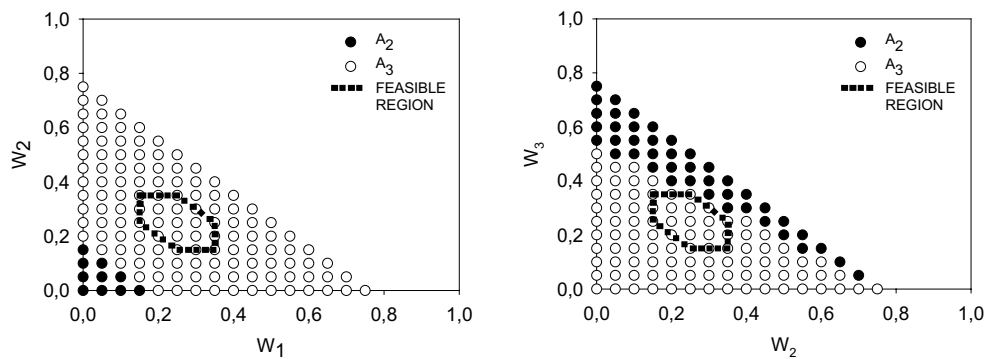


Figure 1. Sensitivity analysis a) varying simultaneously w_1 , w_2 and w_3 and b) varying simultaneously w_2 , w_3 and w_4 .

As shown in Figure 1, for each (x,y) pair, the option with the best score is plotted (Note that the parameter z is not represented but it depends on x and y by the restriction $x + y + z = 0.75$). From the results generated by both sensitivity analyses we conclude that A_3 is the most preferred option for a wide range of situations in the feasible region (in this case study the feasible region is considered as ± 0.10 of the weight value and it is represented with a dotted line), compared to A_2 . Thus the selected option for the first issue will be A_3 . The redesign procedure will continue evaluating the rest of the issues of the reactor section (point of chemical addition, control strategy for iron dosage...) separation section (increase of settling area...) and finally recirculation section (additional recirculation from the anoxic to anaerobic zone)

4. Conclusions

An application of the HDP to re-design activated sludge plants based on a multi-criteria evaluation method has been developed. The multi-criteria method allows the inclusion of different objectives and the HDP reduces the design problem to a set of issues that follow a predefined order (reactor, separation and recirculation). A sensitivity analysis has been applied to test the robustness of the decision between the competing options and it has proved to be a useful tool to support and complement the decision procedure.

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