Design of Wastewater Treatment Plants Using a Conceptual Design Methodology

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This study presents a systematic conceptual design methodology for urban wastewater treatment plants (WWTP) that combines a hierarchical decision process with the mathematical modeling of the WWTP. An existing WWTP (Granollers WWTP, Spain) was chosen as a case study to apply the proposed design methodology. The design methodology carries with it three sets of advantages: (1) the systematic evaluation of the different alternative designs with respect to a set of criteria, (2) the integration of mathematical modeling in the evaluation of the different alternative designs, and (3) the maintenance of a record of the design process. Finally, a redesign example that shows how the records of a design process can be used to identify the decisions affected by a change in the design objectives is also presented.

1. Introduction

The design of chemical processes is a complex activity involving synthesis, analysis, and evaluation, which in turn involve decision making. Once a chemical route has been decided upon, the process continues with the selection of its constituent units and their interconnections onto a flowsheet depicting the transformation of raw materials into the desired products, followed by the simulation and analysis of this flowsheet. The design process is complicated because of the great number of alternatives that can be generated and evaluated against criteria such as cost, safety, environmental constraints, technical and social factors, etc. Douglas[1] estimated that there are between 10^4 and 10^9 alternative flowsheets in a typical chemical process design problem.

Conceptual design has received a lot of attention during the past decade and a half. After the seminal work of Douglas, the methodology known as *hierarchical decision process*[2] proposed to break down the conceptual design process, often very long and complex, into several tasks that were much simpler to analyze by including new levels of detail successively. First, the background is defined, namely, the design problem itself together with the objectives that are to be satisfied. Then comes the design of the reaction section; this is the part of the process where the raw materials will be transformed into products. The output of the reaction section is a mixture of products, subproducts, and unreacted reactants. The products have to be separated from the rest of the components, and the unreacted reactants have to be recycled into the reactor. For this reason, the reactor section has a great influence on the system of separation and recycling. Finally, the overall process is analyzed to explore the opportunities for energy integration.

There are several computer-based support tools for chemical flowsheet synthesis.[3−5] Rodriguez-Roda et al.[6,7] presented one such tool that is concerned specifically with the design of wastewater treatment plants and shows the potential advantages of working with a design support tool such as KBDS (Knowledge Based Design System). However, it does not explore the full implications of mathematical models during design.

Wastewater treatment plants (WWTP) can be seen as a kind of (bio)chemical process. They can be classified into physical−chemical plants and biological plants. In physical−chemical plants, wastewater is purified using physical processes plus the addition of chemical products that precipitate out the pollutants in the wastewater. In contrast, in biological plants, the wastewater is purified using microbial growth processes. Generally, different combinations of physical, chemical, and biological operations make up the process diagram of a wastewater treatment plant.

Good management of wastewater treatment processes aims at ensuring a degree of purification sufficient to comply with the legislative limits on water discharge while, at the same time, keeping costs, both environmental and financial, at a minimum. With these requirements in mind, several studies have attempted to apply support tools to WWTP operation. Examples are control systems,[8] simulation models,[9] and knowledge-based systems.[10] It is worth noting, however, that the design stage of a process is at least as important as its operation and that operational problems often exist because of inadequate design. Up to now, wastewater treatment plant design studies have focused on the simulation and analysis of the plant flowsheet[11] rather than on its synthesis, even though the latter is the stage where some of the most important economic, social, technical, and environmental[12] decisions are made.

The aim of this study is to present a systematic conceptual design methodology for urban WWTPs that combines the hierarchical decision process with the mathematical modeling of the WWTP. This methodology is implemented using two software tools: a decision rationale management system (DRAMA[13]) and a wastewater treatment plant simulation program (GPS-X[14]).

Application of the hierarchical decision process to WWTP design is possible because of structural similari-

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10.1021/ie010652b CCC: $22.00
Published on Web 09/05/2002

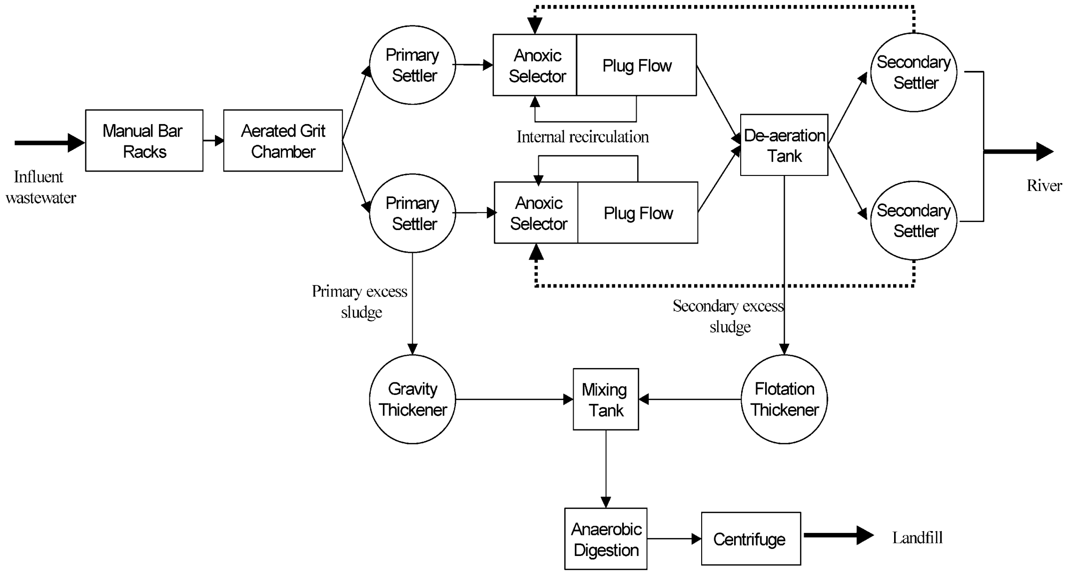

Figure 1. Flowsheet of the Granollers wastewater treatment plant.

ties with chemical processes. In a WWTP, as in other chemical processes, a transformation is made in the reaction section in order to obtain a product, and separation and recycle sections are also necessary. The design process does, however, need to be modified to cater for the differences that exist between the two types of processes. The most important difference is that chemical processes result in a wider variety of flowsheets because they involve many more types of products and raw materials. In contrast, WWTPs always have the same function expressed in the same input-output structure. Thus WWTPs always have a similar process flowsheet. As a result, design of WWTPs starts with an established flowsheet structure, and the hierarchical decision process is applied to the selection of the different units that constitute the flowsheet structure.

Another important and subtle difference is that the main objective of chemical processes is economic, although environmental factors are important. In contrast, the main objective of a WWTP is environmental, although economic factors are important. Finally, a WWTP receives a raw material stream (wastewater) that is highly variable both in quality and quantity. So, it is important to put special emphasis on process control and flexibility aspects.

This article is organized as follows: first, a description of the WWTP used as a case study is given. Then the proposed methodology for flowsheet design of wastewater treatment plants is presented, together with a discussion of how the methodology was applied to the case study and how mathematical modeling was incorporated into the design process to evaluate the different design alternatives. Next, a comparative analysis between the resulting structure and the structure of an existing WWTP plant is performed. Finally, a scenario of a change in legislation is presented to show the advantages of systematisation of the design process.

2. Description of the Installation Used as a Case Study: Granollers WWTP

The plant, built in 1992, initially worked with preliminary and physical−chemical treatment of organic matter and removal of suspended solids. In April 1998, it was converted to biological treatment and physical−chemical treatment was completely replaced. Later on, the plant was retrofitted to the current Ludzack-Ettinger configuration.[15] As a result, this facility now provides preliminary, primary, and secondary treatment to remove the organic matter, suspended solids, and, under some conditions, nitrogen contained in the raw wastewater of about 130 000 inhabitant equivalents. The raw material influent comes from a combined sewer.

Table 1. Average Input and Operation Values of the Granollers Wastewater Treatment Plant from a Historical Database Recorded during Two Years

influent	inflow ($m^3\ d^{-1}$)	22 142
	BOD_5 ($g\ m^{-3}$)	420
	COD ($g\ m^{-3}$)	766
	SS ($g\ m^{-3}$)	292
	TN ($g\ m^{-3}$)	97
biological reactor	air flow ($m^3\ d^{-1}$)	150 000
	dissolved oxygen ($g\ m^{-3}$)	2
	MLSS ($g\ m^{-3}$)	3000
	MLVSS ($g\ m^{-3}$)	2200
secondary settler	wasted flow (W) ($m^3\ d^{-1}$)	1046
	external recycle flow (R) ($m^3\ d^{-1}$)	5900
	$MLSS_{waste}$ ($g\ m^{-3}$)	2847
	$MLVSS_{waste}$ ($g\ m^{-3}$)	2135
	$MLSS_{Recirc}$ ($g\ m^{-3}$)	9020
	$MLVSS_{Recirc}$ ($g\ m^{-3}$)	6780

Typical concentrations in the Granollers WWTP inflow were obtained from a statistical analysis of the historical database. Table 1 shows average of the input and operational values available through a historical database recorded during two years.[16]

The overall wastewater treatment process at the Granollers WWTP can be divided into two main treatment lines: water and sludge. Three stages can be distinguished in the water treatment line: preliminary treatment, primary treatment, and secondary (biological) treatment. The sludge treatment line consists of the following steps: thickening, anaerobic digestion, and dewatering (Figure 1).

The preliminary treatment includes screening for the removal of coarse particles (manual bar racks) and an aerated grit chamber. Wastewater is then pumped to the primary and secondary treatment units.

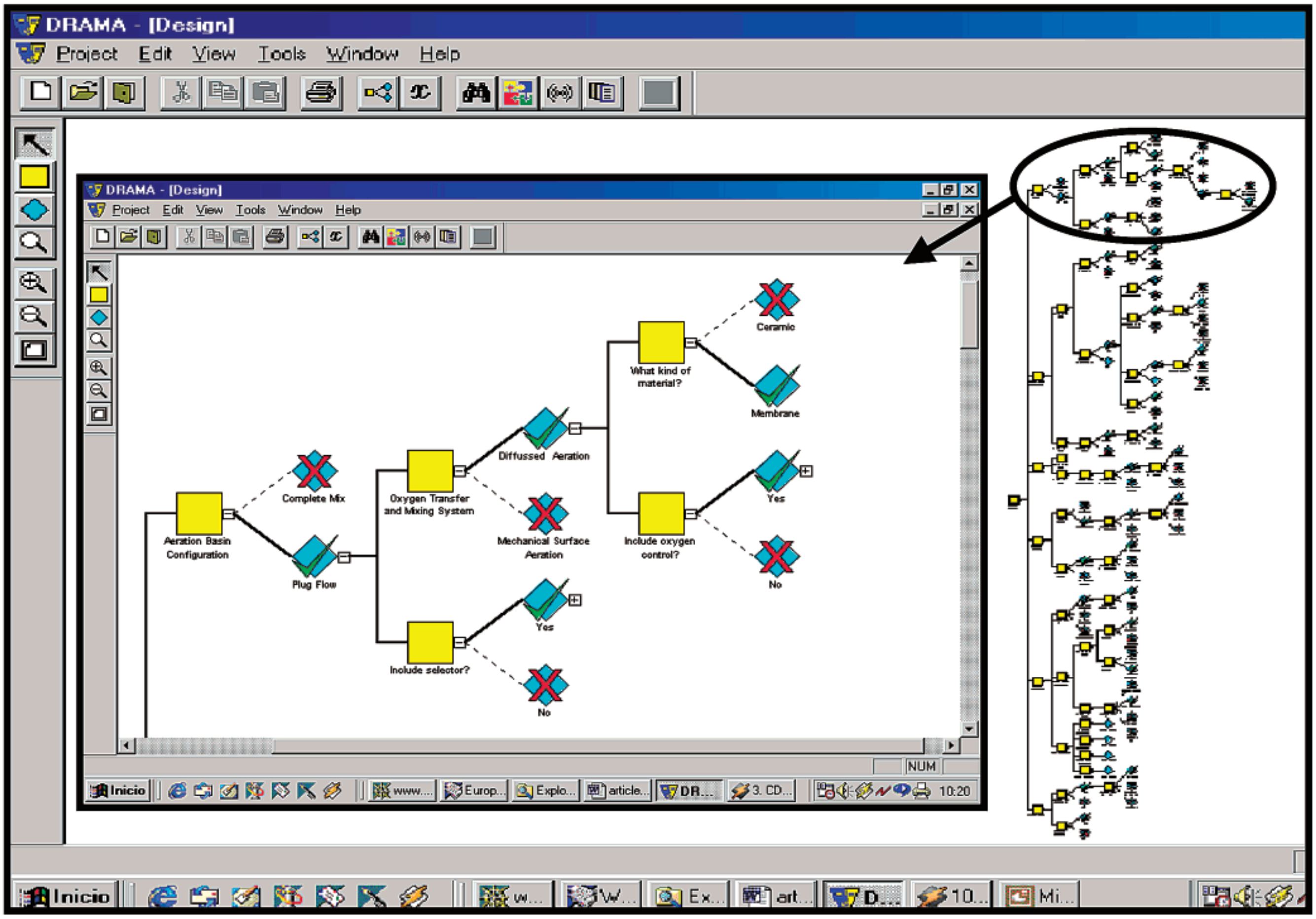

Figure 2. Representation of the decision structure in DRAMA.

The primary treatment consists of two circular primary settlers with a sludge-scraping mechanism for the product of physical sedimentation of suspended solids (previously used for the physical–chemical treatment). Physical–chemical treatment has been abandoned, except in case of heavy rain. Occasionally, one of the primary settler tanks is utilized as a flow equalization basin (to avoid hydraulic shocks and unstable loads). Primary excess sludge is intermittently purged to the sludge line.

After the primary treatment, all of the wastewater is sent to the secondary treatment, where it is distributed into two parallel and symmetric lines of a conventional activated sludge process.[15] This consists of two suspended growth bioreactors followed by two secondary settlers. The compartmentalized conventional plug flow bioreactors have an anoxic selector located at the beginning of the tank, and an internal recycle. At the exit of both bioreactors, the activated sludge is collected in a small deaeration tank from which the purge of secondary excess sludge is taken. From the deaeration tank, the sludge is sent to the secondary settlers, where it is separated from the treated water. The water is discharged to the river, while the concentrated sludge is recycled back into the bioreactors.

Excess sludge purged from the water line is thickened in the first step of the sludge treatment line (the primary by gravity and the secondary by flotation). Then it is mixed and sent to the anaerobic digestion unit where, after stabilization of the sludge with ferric chloride and lime, it is drained and dried. This process is conducted by means of two centrifuge units. Finally, the dried sludge is disposed of in a controlled landfill.

3. Methodology

This section details the methodology that we propose to design the flowsheet of a WWTP. The methodology, which combines the hierarchical decision process with a mechanistical model of the process, was implemented with the help of a decision support tool (DRAMA). This tool facilitates a systematic design process by keeping a record of the design decisions together with the design objectives and the alternatives that were generated to satisfy those objectives. Thus, DRAMA uses an object/oriented database and a graphical user interface to store and structure reasoning related to design or any other activity where decisions are made. The reasoning is recorded in the form of the arguments for and against different alternatives (the argumentation). The structure of the argumentation is based on the established IBIS (issue/based information systems[17]) approach, augmented in several ways to make it appropriate for engineering design. In particular, supports have been added for tracking goals, decomposing complex decisions into a number of simpler subdecisions and the use of quantitative as well as qualitative argumentation. The context of the argumentation can be preserved by means of hypertext links between DRAMA argumentation objects and other electronic design documents, e.g., flowsheets, spreadsheets, and databases. DRAMA also provides facilities for searching, consistency checking, impact analysis, and report generation.

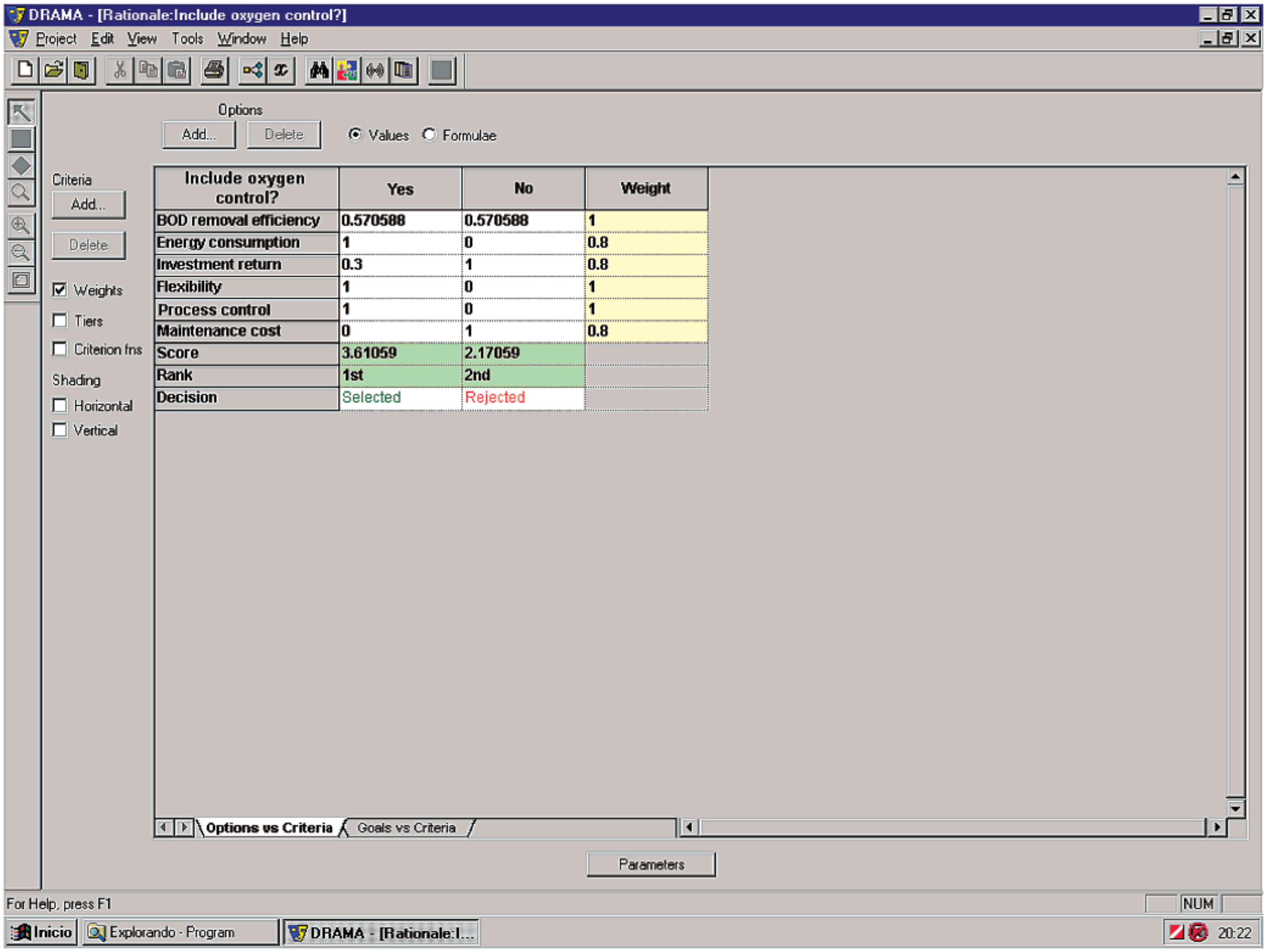

Figure 3. Options versus Criteria window.

The first step of the design methodology carried out in our study was to define the objectives. According to these objectives, some issues arose. As justified in the Introduction, the issues always concerned the type of unit configuration and never the flowsheet structure itself.

The third step was to select the alternatives to solve each issue and the criteria to evaluate the design alternatives. These criteria were specific to each decision. Different weighting factors were assigned to determine the importance of each criterion. A number of meetings with experts in the field of WWTP design and operation from different engineering companies were set up until an agreement on the economical and social criteria used in our design (the nature of each criterion, its relative weight, and the scoring values) was reached. The strong link between criteria and design objectives was also recorded in our procedure ("goals versus criteria" window in DRAMA).

Once the alternatives and criteria were selected, the evaluation of alternatives was carried out. Values between 0 and 1 were used to score the competing alternatives with respect to each criterion. Score values were often fixed by the designers, but sometimes they were calculated as functions of other parameters. GPS-X, a WWTP simulator, was used to obtain the operational information for each alternative. GPS-X is a commercial piece of software that includes all of the models developed by the task group on Mathematical Modeling for Design and Operation of Biological Wastewater Treatment.[18] The way in which GPS-X is integrated in the process design is explained in section 4.4.

Finally, the alternatives were ranked according to the score obtained from the evaluation (Figure 3). The alternative with the highest score was the one recommended by the process design, but the final decision rested on the process designer.

The same methodology was uniformly applied to solve each issue until the final WWTP design was achieved. A branching network of decisions was developed to represent the design process (Figure 2).

The objectives were organized in a network where each objective could be refined as the decision process took place or new objectives could be generated (see

4. Case Study

4.1. Initial Design Objectives. The main objective proposed in carrying out the design was to comply with the limits fixed by the European directive (91/271/CEE) concerning water discharge and sludge disposal while at the same time minimizing technical problems, and construction and operation costs, as well as reducing environmental and social impacts (Table 2).

4.2. Design Alternatives. Design alternatives are shown within the network of decisions that represent the design process (Figure 2). The branches of the network follow a logical order based on the hierarchical

Table 2. Design Objectives

OBJ1: comply with the limits fixed by the European regulation 91/271/CEE for water discharge in nonsensitive areas:

1. $BOD_5 < 25$ g m^{-3}
2. COD < 125 g m^{-3}
3. SS < 35 g m^{-3}

OBJ2: minimize technical problems

1. flexibility
2. robustness
3. control
4. compatibility *between different units*

OBJ3: minimize investment and operation costs.

OBJ4: minimize environmental impact of:

1. energy and raw materials consumption
2. atmosphere emissions
3. sludge generation

OBJ5: minimize social impact of:

1. soil occupation
2. visual aspect
3. noise
4. odors

OBJ6: comply with the limits fixed by the European regulation 91/271/CEE for sludge disposal. (Refinement of Obj.1):

1. dehydrate and stabilize sludge
2. sludge water < 75%
3. volatile suspended solids (VSS) < 40%

decision process developed by Smith[2] to break down the conceptual design process. The decision structure behind the development of the complete structure (Figure 2, Table 3) goes through stages. To pass from one stage to the next, a choice between two or more design alternatives must be made. The decision process for choosing one of the alternatives is explained in detail in the next section.

4.3. Evaluation of the Alternatives. Evaluation of the alternatives was made while keeping in mind various criteria of economical, social, environmental, and technical nature (Table 4). Each criterion had a different degree of importance in the design and was accordingly assigned a weighting value.

The evaluation of alternatives was recorded by means of two windows in DRAMA, “Options versus Criteria” (Figure 3) and “Goals versus Criteria”. The Options versus Criteria window shows a matrix in which the columns represent the options to be evaluated and the rows show the criteria to be used during evaluation. The last column is reserved for the weight or importance of each criterion within the design (see, for example, Table 4). It is important to point out that assigning weights to the criteria is optional. The options are automatically ranked according to the score obtained (see the “Rank” row in Figure 3).

As an example, Figure 3 shows the two options considered for the issue “Do we include oxygen control in the reactor?” (Table 3, D4) and the six criteria used in their evaluation: BOD_5 removal efficiency (C-Tech3), energy consumption (C-Env1), investment return (C-Econ1), flexibility (C-Tech6), process control (C-Tech9), and maintenance cost (C-Econ2). The recommended option was to include oxygen control.

The Goals versus Criteria window has the function of recording the relationship between the criteria in the current evaluation and the objectives proposed for the design. In this case, apart from the objective, “Minimise social impact” (OBJ5), the rest of the objectives have been related with at least one of the criteria selected to assess this decision. In the example, the objective of minimizing technical problems (OBJ2) is related with the BOD_5 removal efficiency (C-Tech3), Flexibility (C-Tech6), and Process Control (C-Tech9) criteria.

The “Design rationale” option[19] also allows the introduction of parameters, i.e., variables set by the user or imported from other software (databases and simulation programs), for the evaluation of design alternatives. For example, as will be shown in section 4.4, some of the criteria used to decide whether to include oxygen control depended on parameters imported from the simulation program GPS-X.

Last, another possibility of DRAMA is the “Associated Parameters“ function, which was of particular use in recording our design. This function enables one previously chosen unit of the process to determine the selection of a later unit. One example of this association is the decision on whether to include sludge stabilization in the sludge treatment (D21). One of the criteria considered when resolving this question was the type of biological reactor in which the organic material in the wastewater had decomposed. So, if the reactor was of the “complete mix” or “plug flow” type, the alternative of including sludge stabilization obtained the highest score with respect to this criterion, whereas if the reactor was of the “oxidation ditch” type, the alternative of not including sludge stabilization received the highest score.

The way in which DRAMA integrates the evaluation of alternatives improves the consistency of the design by ensuring that each criterion is linked to one of the objectives. This enables DRAMA to follow one particular scheme of evaluation for all design decisions. It also enables it to record all of the reasoning followed in the decision process up to the final design structure. Bearing in mind that changes can arise in legislation, economy, and society, it is quite possible that the plant may need to be redesigned in the future. This is an important observation because all of the features described above are of great value in a support tool for process design and redesign. Because a “corporate memory” is maintained, it is possible to reuse part of the decision making process and hence avoid repeating calculations, deliberations, etc., to focus only on the decisions affected by the change and their dependent decisions.

4.4. Mathematical Modeling and Its Integration within the Hierarchical Decision Process. Simulations were used to evaluate different alternatives with respect to operation related criteria. All of the design alternatives were simulated with a wastewater influent profile of 170 days, representative of the historical database from the Granollers treatment plant.

Table 5 shows the mean, standard deviation, minimum, and maximum of the input profile variables selected to carry out the simulations. For reasons of clarity, Figure 4 shows only the input profile for 10 of the 170 days simulated, but all 170 days were used in the evaluation of the alternative design.

Following the same example chosen in section 4.3 concerning the decision as to whether to include oxygen control in the reactor (Table 3, D4), simulation results were used to evaluate the two alternatives with respect to the criteria of BOD_5 removal efficiency (C-Tech3), energy consumption (C-Env1), and investment return (C-Econ1; Table 4). Other criteria such as flexibility

Table 3. Summary of the Application of the Hierarchical Decision Process to Wastewater Treatment Plant Design

	decision	alternatives
	Wastewater Treatment: Reactor Section	
D1	what kind of biological reactor?	plug flow
		complete mix
		oxidation ditch
D2	what kind of air supply?	diffusers
		turbines
D3	what kind of diffuser material?	membranes
		ceramics
D4	do we include oxygen control?	yes
		no
D5	what kind of set points?	fixed throughout the reactor
		progressive throughout the reactor
D6	do we include setpoints revision?	yes
		no
D7	do we include selector?	yes
		no
D8	what kind of selector?	aerobic
		anoxic
		anaerobic
	Wastewater Treatment: Separation Section Prior to the Reactor	
D9	do we include preliminary treatment?	yes
		no
D10	do we include removal of coarse particles?	yes
		no
D11	do we include grit remover?	yes
		no
D12	what kind of grit remover?	vortex
		aerated grit chamber
D13	do we include flow equalization?	yes
		no
D14	do we include primary treatment?	yes
		no
D15	shape of primary sedimentation tank?	circular
		rectangular
	Wastewater Treatment: Separation Section after the Reactor	
D16	shape of secondary sedimentation tank?	circular
		rectangular
D17	what type of secondary sedimentation tank?	suction
		scraper
	Wastewater Treatment: Recycling and Wasting Section	
D18	do we include external recycle?	yes
		no
D19	do we include internal recycle?	yes
		no
D20	what type of pumps?	centrifugal
		progressive cavity
	Sludge Treatment: Reactor Section	
D21	do include sludge stabilization?	yes
		no
D22	what means of sludge stabilization?	aerobic
		anaerobic
		chemical stabilization
	Sludge Treatment: Separation Section Prior to the Reactor	
D23	means of thickening the primary sludge?	gravity
		flotation
D24	means of thickening the secondary sludge?	gravity
		flotation
	Sludge Treatment: Separation Section after the Reactor	
D25	means of dewatering?	belt filter presses
		pressure filter presses
		drying beds
		centrifuges

(C-Tech6), process control (C-Tech9), and maintenance cost (C-Econ2) were also considered but are not covered by the simulation model used and thus are not discussed in this section.

To evaluate the alternatives, kinetic and settling parameters obtained from a previous calibration of the Granollers WWPT were used.[16] To carry out the calibration, records of two years of the influent and effluent profiles and process operating conditions were retrieved from the historical database.

The alternatives were simulated using a conventional plug-flow reactor, previously chosen, in the form of three complete mix reactors in a series (plug flow reactors are modeled in GPS-X as series of continuous stirred tank

Table 4. Criteria Used for the Design and the Relative Weight Assigned to Each Criteria

environmental criteria (C-Env)		weight
C-Env1	energy consumption	0.8
C-Env2	raw materials consumption	0.8
C-Env3	sludge production	0.8
C-Env4	supernatants quality	0.8
C-Env5	effluent quality	0.8
C-Env6	sludge quality	0.8
technical criteria (C-Tech)		**weight**
C-Tech1	susceptibility to shock loads	1
C-Tech2	filamentous bacteria growth	1
C-Tech3	DBO_5 removal efficiency	1
C-Tech4	TN removal efficiency	1
C-Tech5	compatibility between different unit processes	1
C-Tech6	flexibility	1
C-Tech7	sludge pathogen removal	1
C-Tech8	sludge volatile solids removal	1
C-Tech9	process control	1
economic criteria (C-Econ)		**weight**
C-Econ1	investment return	0.8
C-Econ2	maintenance cost	0.8
C-Econ3	operation cost	0.8
C-Econ4	cost of solid waste disposal	0.8
social criteria (C-Soc)		**weight**
C-Soc1	land occupation	0.5
C-Soc2	odors	0.5
C-Soc3	noise	0.5
C-Soc4	visual impact	0.5

Table 5. Input Variables of the 170 days of the Simulation

	input (m^3 d^{-1})	BOD_5 (g m^{-3})	COD (g m^{-3})	SS (g m^{-3})
mean	23672.9	426.8	787.7	329.5
std. dev.	7095.2	167.1	240.3	103.8
min.	7564	62.7	221.1	88
max.	62035	1867.2	2859.1	1071.6

reactors (CSTRs)). Three CSTRs were used to account for the fact that the reactor in Granollers has three compartments. The IAWPRC Activated Sludge Model No. 1[20] and a 10-layer one-dimensional settler model [21] were used to simulate the biological reactions and the settling process, respectively.

For the alternative "No oxygen control", we fixed an air supply of 150.000 m^3 d^{-1} divided equally among the three compartments. The air supply flow was calculated to maintain a minimum concentration of oxygen of 2 g m^{-3} throughout the aerated tank.[22] In other words, the oxygen requirements of the reactor in relation to the properties of the influent at any one time are not taken into account. Figure 5 shows the dissolved oxygen present in the reactor at each of the three compartments (during the 10 days chosen to illustrate the simulations). In the first compartment, oxygen concentrations of less than the minimum (2 g m^{-3}) can be seen. Oxygen levels increase in the second compartment to reach 6 g m^{-3} in the third compartment. This trend is due to the fact that the oxygen requirements at the inlet of the plug-flow reactor are higher than those in the final compartments.

For the alternative with oxygen control, a control of type PID with a set point of 2 g m^{-3} of dissolved oxygen throughout the reactor was considered. In this case, air flow consumption was related to the oxygen requirements at any time. Thus, the air supply required by the first compartment in order to maintain an oxygen concentration of 2 g m^{-3} was greater than that of the other two, whereas that of the second compartment was generally greater than that of the third compartment (Figure 6).

In terms of the energy consumption criterion (C-Env1), the alternative with oxygen control consumed less energy than the alternative without oxygen control. This is because the oxygen control device allowed the air supply to be adjusted to the oxygen requirements, which in turn are related to the properties of the influent stream at any one time. Savings of up to 65 000 m^3 of air a day (about 0.026 Kw h per m^3 of air) were observed (Figure 6). It is important to note that the removal efficiency of organic material (C-Tech 3), shown in the output profile of the concentration of biological organic matter in Figure 7, was the same in both cases because oxygen was not a limiting variable.

Some simulation results were introduced as parameters of the formulas used to evaluate the proposed alternatives with respect to the various criteria. The parameters used in the evaluation of the decision to include oxygen control were as follows:

CEcon1c: the number of years to get a return on the installation investment for the alternative with oxygen control;

CEcon1nc: the number of years to get a return on the installation investment for the alternative with no oxygen control;

CEnv1c: the number of days in which the alternative with oxygen control consumed less energy than the alternative with no oxygen control;

CEnv1nc: the number of days in which the alternative with no oxygen control consumed less energy than the alternative with oxygen control;

CTech3c: the number of days in which the alternative with oxygen control complied with the legislative limits for the elimination of organic matter as measured by DBO_5;

CTech3nc: the number of days in which the alternative with no oxygen control complied with the legislative limits for the elimination of organic matter as measured by DBO_5.

TDS: the total days of simulation.

In this case, the parameters are constant values, but their values can be calculated through formulas or imported from an external routine.

The efficiency of the removal of organic matter (C-Tech3) was evaluated using CTech3c and CTech3nc with respect to TDS; for both alternatives (with and without oxygen control), the values of CTech3c and CTech3nc were 97 days out of the 170 days simulated. Energy savings were evaluated using CEnv1c and CEnv1nc with respect to TDS; in this case, the results showed that the alternative with oxygen control always consumed less energy. Thus, the value for CEnv1c was 170 days out of the 170 days simulated, whereas the value for CEnv1nc was 170 days out of the 170 days simulated. Last, the investment return on the installation was evaluated by applying a value function[23] to CEcon1c and CEcon1nc. The value function used in this case was a linear function which mapped the values of CEcon1c and CEcon1nc into a range from 0 (represent

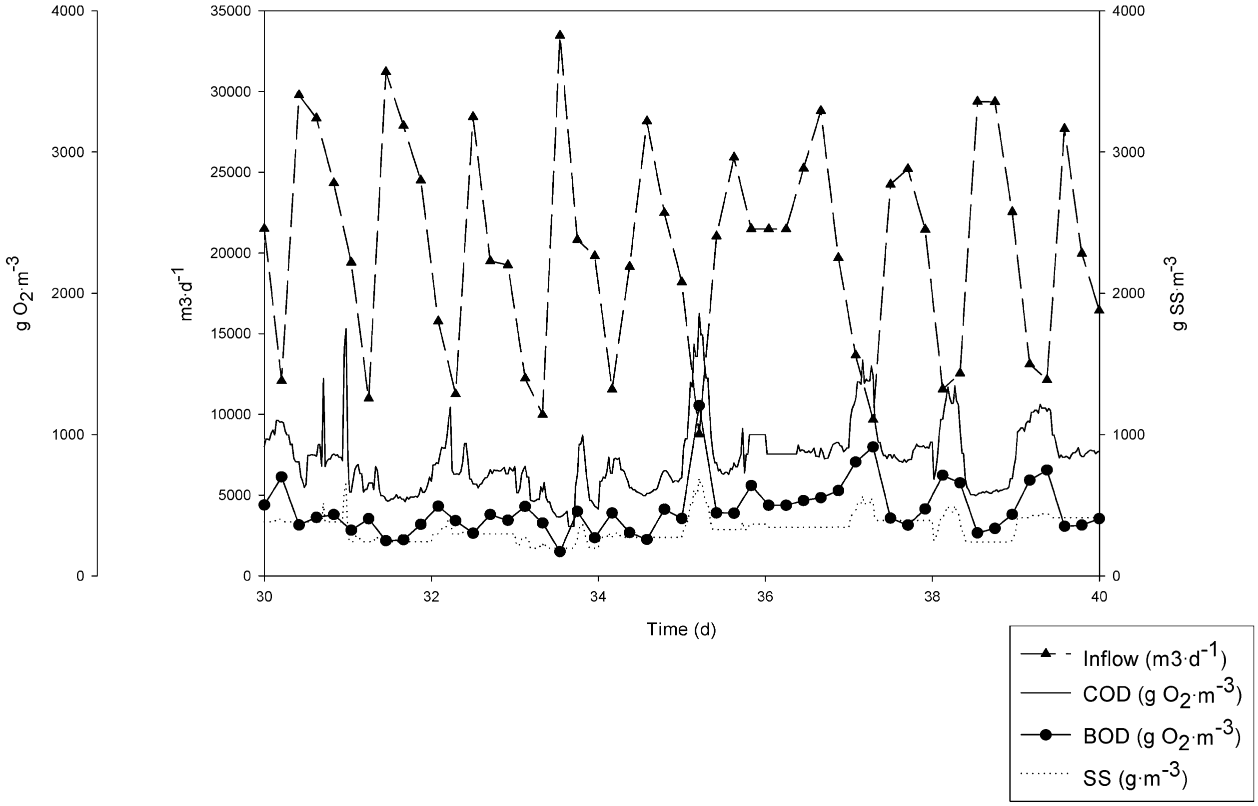

Figure 4. Input profiles for inflow, COD, BOD_5, and SS.

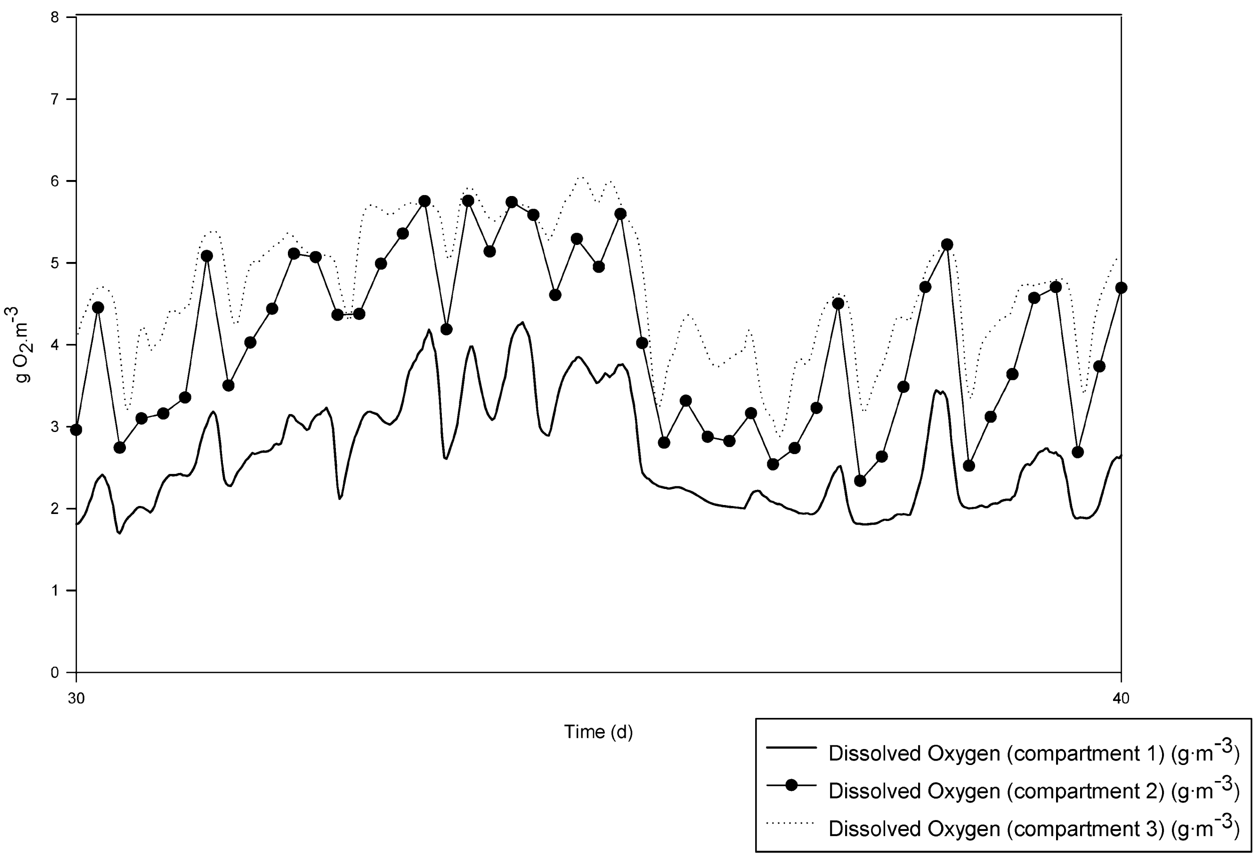

Figure 5. Alternative without oxygen control: dissolved oxygen in the biological reactor.

ing the worst situation considered, i.e., 10 years of investment return) to 1 (representing the best situation considered, i.e., 0 years of investment return). For the alternative with no oxygen control, the result of applying this value function was 1 (the value of CEcon1nc was 0 years of investment return); for the alternative with

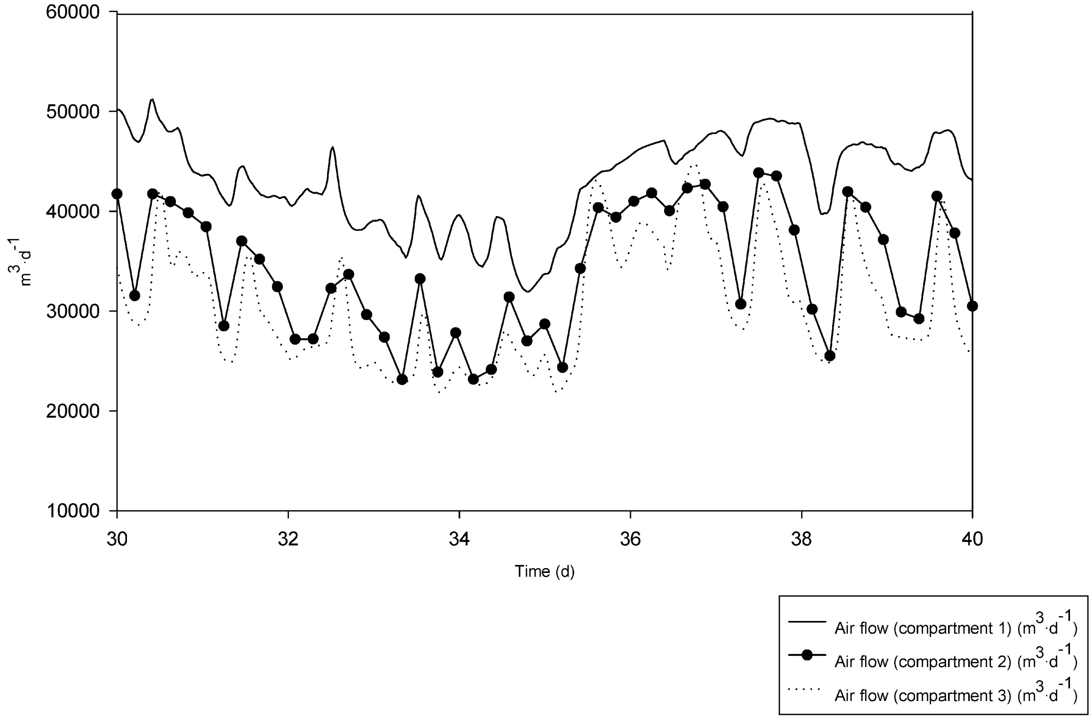

Figure 6. Alternative with oxygen control: air flow consumption in the biological reactor.

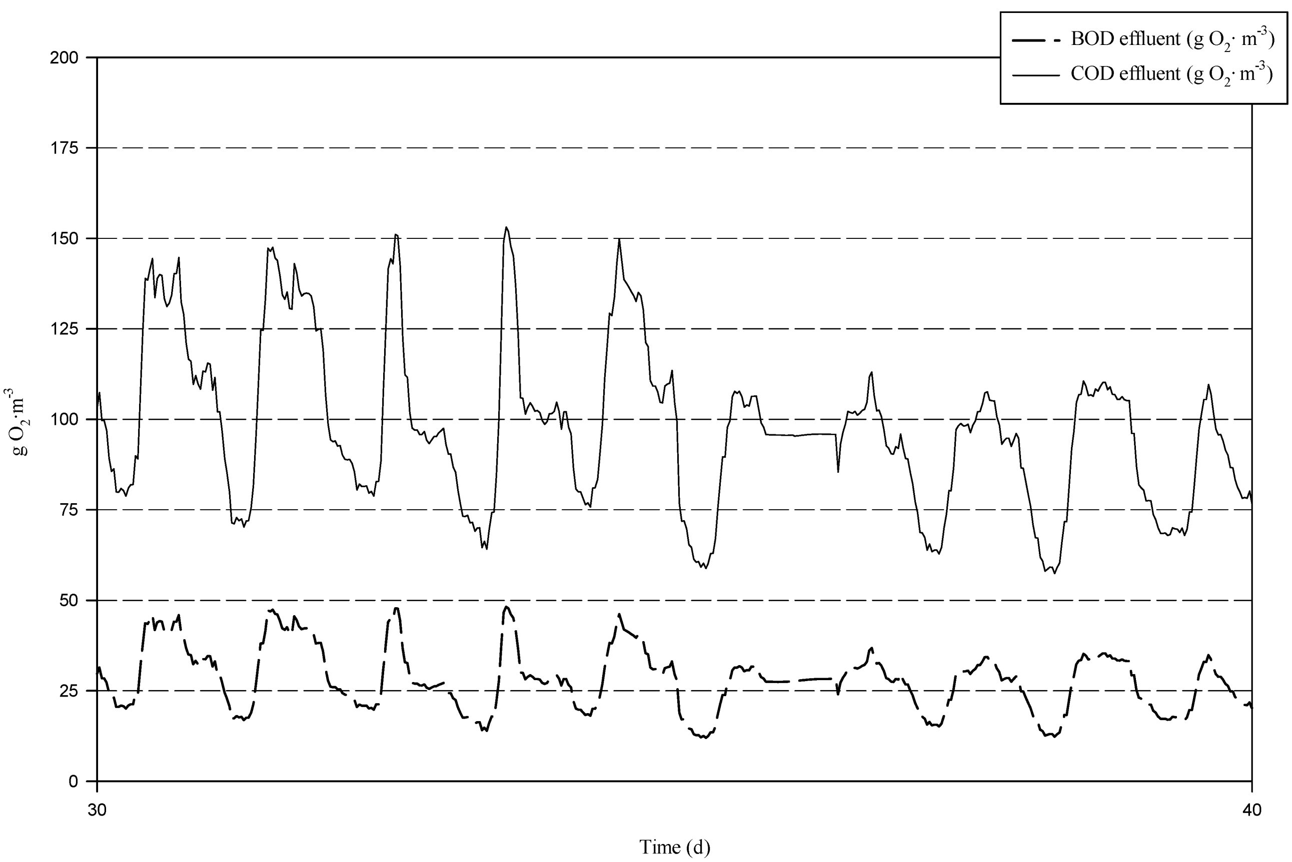

Figure 7. Alternatives with and without oxygen control: COD and BOD_5 output profile.

oxygen control, the result was 0.3 (the value of CEcon1c was 7 years of investment return).

In the end, and taking also into account the criteria of flexibility (C-Tech6), process control (C-Tech9), and maintenance cost (C-Econ2; Figure 3), the alternative with oxygen control was the one that scored the highest. Following the hierarchical decision process, and assuming this alternative was selected, the next decision would concern the type of oxygen control set point to install in the reactor, i.e., fixed or progressive (Table 3, D5). In this case, it was decided to install a control device with a progressive set point of oxygen.

DRAMA allows linking decisions to files, figures, web pages, etc. In this case, we have linked Figures 7–9,

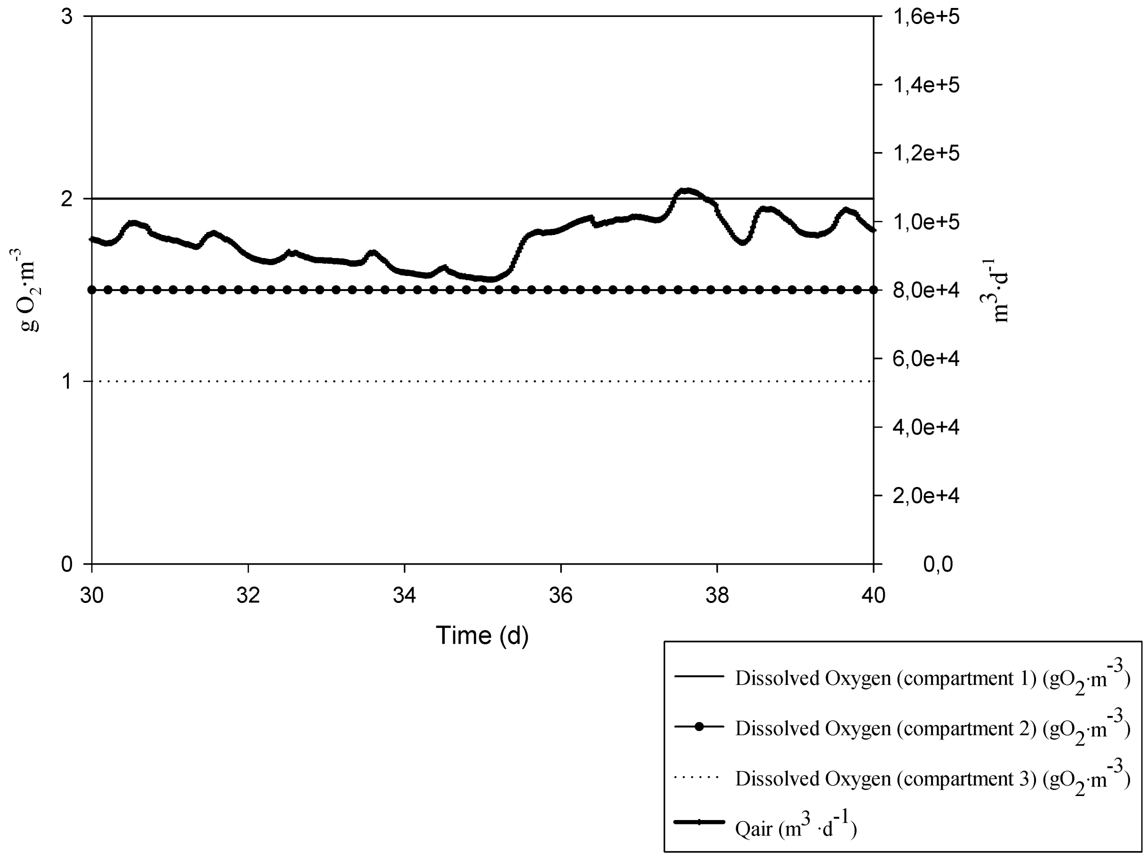

Figure 8. Systematically designed WWTP: dissolved oxygen and air flow in the biological reactor.

which are the results of simulations, with their corresponding alternatives. This is extremely useful for any future understanding of the design.

5. Comparative Analysis of the Resulting Flowsheet and the WWTP of Granollers

All of the decisions in Table 3 were made and recorded as described in sections 4.3 and 4.4. The flow diagram resulting from applying this systematisation of design differed from the plant at Granollers in only a few units of the process. The most important difference was that each of the selected units that made up the flow diagram of the plant designed systematically were justified by a process of evaluation of alternatives and those justifications were recorded. The differences in the flow diagrams of the systematically designed plant and the actual plant at Granollers are summed up in the Table 6. The CAPDET Works software package[24] was used to estimate construction and additional site-specific costs within each unit of the process. When the cost of some units could not be estimated by CAPDET Works (e.g., in the case of the vortex grit removal system), an estimate from experts from local companies was used. In comparison, the cost of the systematically designed WWTP was 9.7% higher than the Granollers facility.

As shown in the table, the aerated grit remover was replaced by a vortex grit removal system in the systematic design. The latter used less energy and had lower construction and maintenance costs while still efficiently removing the grit. A flow equalization basin was added to reduce the effects of variations in the load and to improve efficiency at later stages in the treatment. The anoxic selector was replaced with an anaerobic one because the designed plant did not take into consideration the elimination of nitrogen and, therefore, showed no internal recycling of nitrates toward the selector. As for the supply of oxygen to the reactor, it was decided to include oxygen control with progressive set points in order to avoid nitrification and save energy. The set points from the beginning to the end of the reactor were 2, 1.5, and 1 g m^{-3}.

Finally, both flow diagrams, the actual one and the one designed systematically, were simulated in order to compare their operation. The systematically designed plant required a lower air supply to the reactor and therefore showed energy savings with respect to the Granollers plant (Figures 8 and 9). This is because the progressive oxygen set points allow the air supply to be better adjusted to the oxygen requirements throughout the plug flow reactor.

With regard to the removal efficiency, both of organic matter and of suspended solids, we observed (Figures 10 and 11) that the structure resulting from our study achieved the best results mainly because of the decision to include a flow equalization basin. Flow equalization avoids hydraulic shocks and unstable loads; in particular, it avoids the so-called "washout" of solids to the reactor, which provokes an increase in the concentration of suspended solids, which escape with the effluent. These solids are also responsible for BOD_5 and COD concentrations in the effluent.

6. Impact Analysis Example

In the scenario described in the previous sections, our plant was designed to remove the organic matter and suspended solids below the limits set by the European legislation. However, the total nitrogen limit set by the same legislation was not included as a requirement of

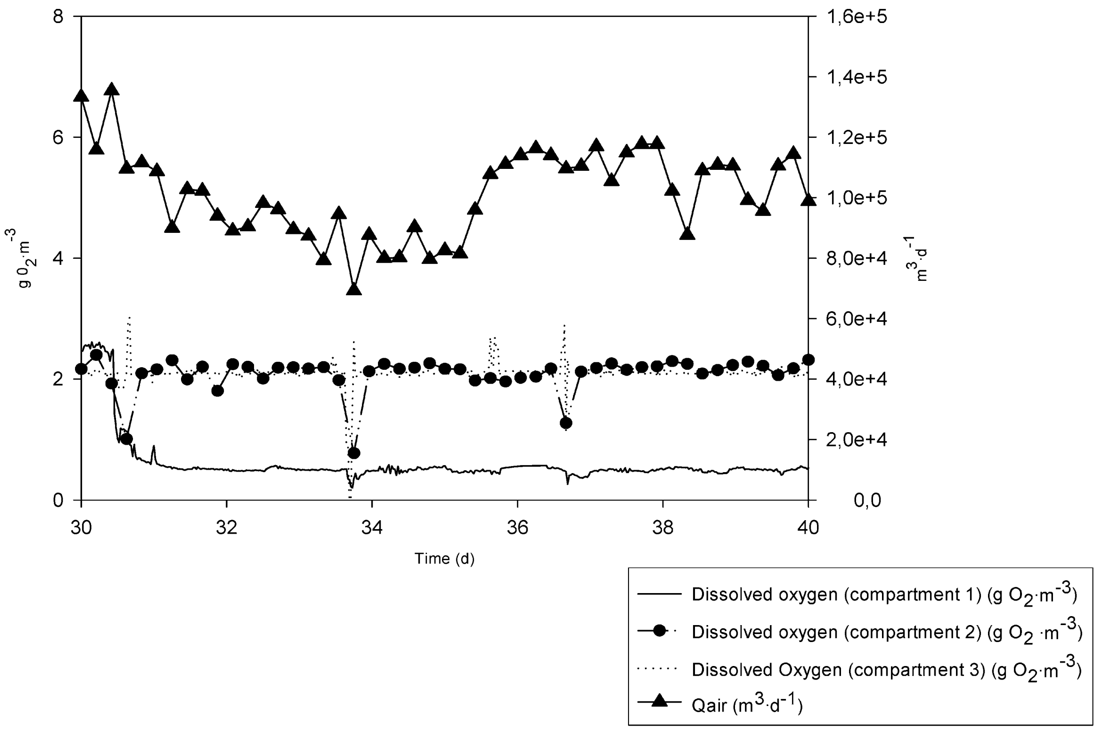

Figure 9. Granollers WWTP: dissolved oxygen and air flow in the biological reactor.

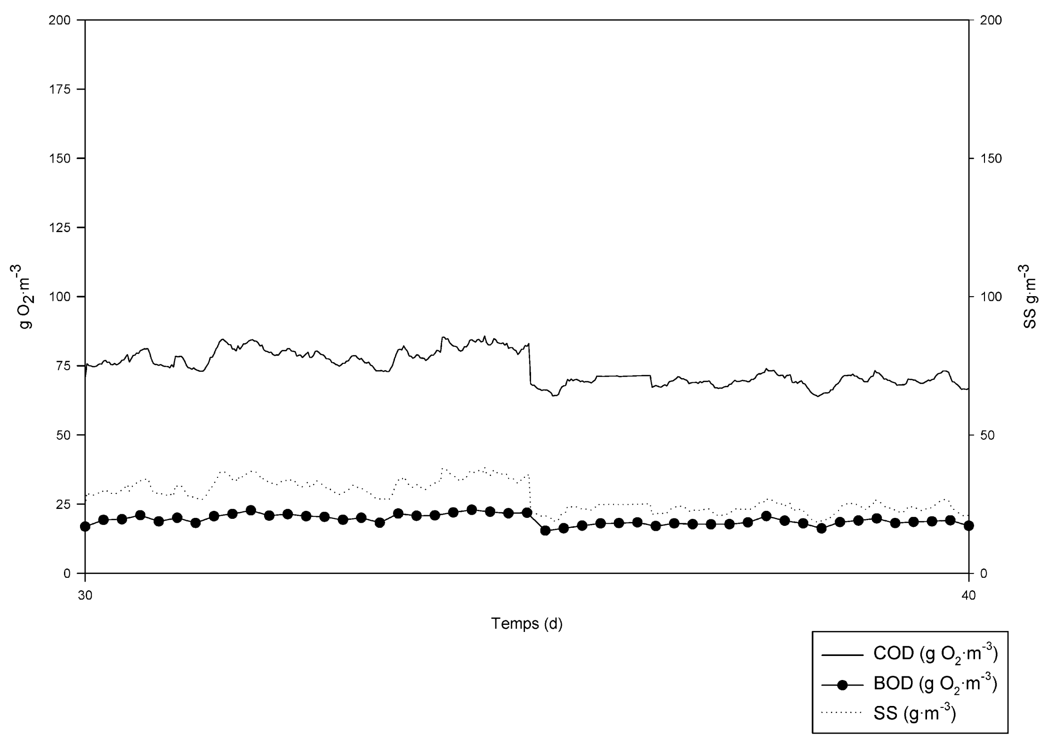

Figure 10. Systematically designed WWTP: COD, BOD_5, and SS output profile.

Table 6. Differences between the Granollers and the Systematically Designed WWTP

unit process	granollers WWTP	systematically designed WWTP
grit removal	aerated grit remover	vortex grit removal system
flow equalization	primary sedimentation tank as a flow equalization basin	flow equalization basin
biological selector	anoxic selector	anaerobic selector
internal recycling	internal recycling	no internal recycling

our design because we wished to compare the result of our design with an existing plant for which we had data (Granollers WWTP, Spain; see section 5). Most plants in Spain were designed before the legislation on total nitrogen was established, as in the case of the Granollers WWTP.

In this section, we show how the records of a design process can be used to identify the decisions affected

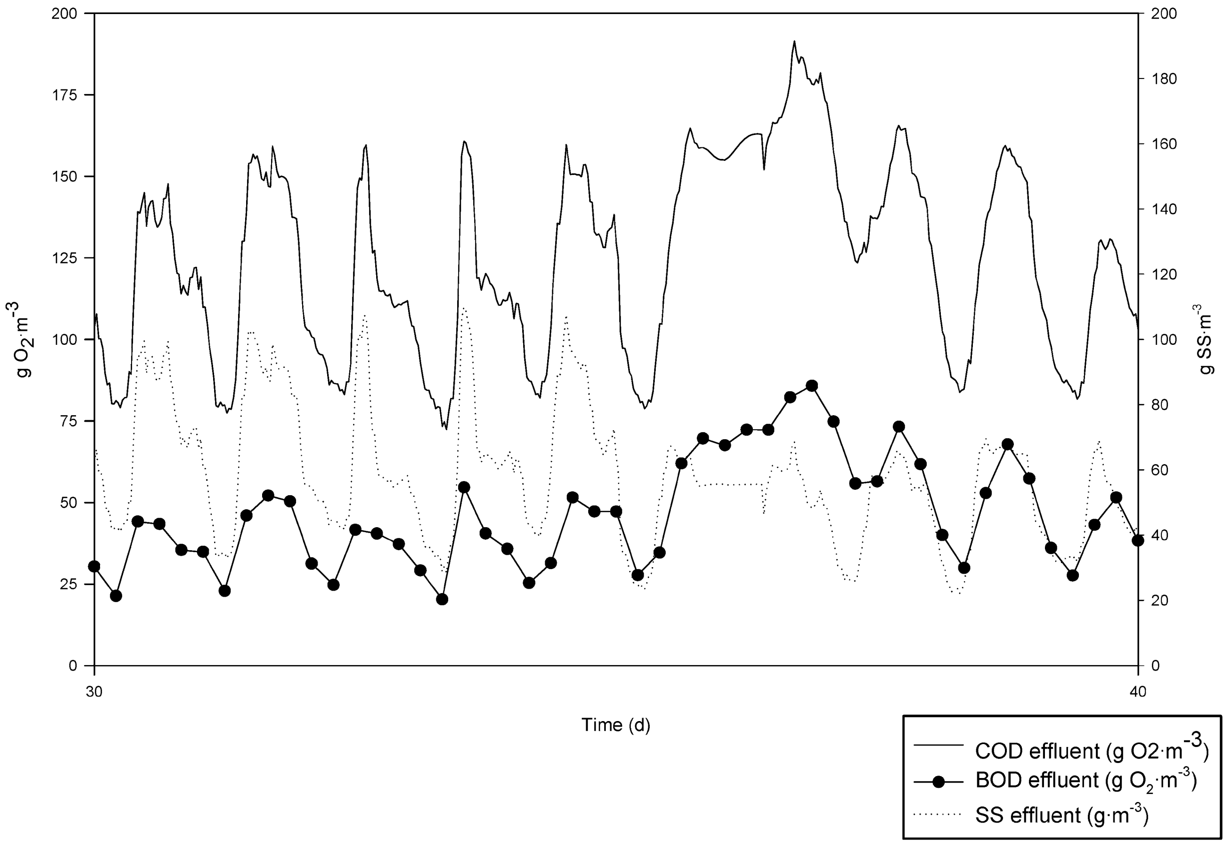

Figure 11. Granollers WWTP: COD, BOD_5 and SS output profile.

by a change in the design objectives. Thus, we propose to add as an additional objective the compliance with the limits fixed by the European legislation concerning nitrogen concentration (10 g m^{-3} of TN). The example is relevant because Spain and other European countries will need to redesign many WWTPs in order to comply with this requirement.

First, we have the option of searching automatically all of the objectives, decisions, and criteria that could be affected by this new requirement. We can see that the keyword "nitrogen" had been included in the design objectives, as wells as in the following decisions and criteria:

What kind of biological reactor? (Table 3, D1)
What kind of diffuser material? (Table 3, D3)
Do we include oxygen control? (Table 3, D4)
What kind of setpoints? (Table 3, D5)
Do we include setpoints revision? (Table 3, D6)
What kind of selector? (Table 3, D8)
Do we include internal recycle? (Table 3, D19)
TN removal efficiency (C-Tech4)
Flexibility (C-Tech6)

An impact analysis was also performed to identify the affected decisions. Impact analyses show which decisions would potentially change when the value of a parameter is modified in order to include new objectives. In this case, we added the NTLeg parameter (total nitrogen limit set by the European legislation). This parameter was changed from 100 g m^{-3} (a value close to the total nitrogen concentration in the influent, see Table 1) to 10 g m^{-3} (the limit set by European legislation). As a result of this modification, and according with the impact analysis calculations, it was concluded that the following decisions would potentially be affected in the following way:

In the decision "Do we include setpoints revision?" (Table 3, D6), the alternative "no" would change to the alternative "yes".

In the decision "What kind of selector?" (Table 3, D8), the alternative "anaerobic" would change to the alternative "anoxic".

In the decision "Do we include internal recycle?" (Table 3, D19), the alternative "no" would change to the alternative "yes".

These results indicate the designer which decisions should be revisited. Final decisions rest, of course, on the designer.

7. Conclusions

The proposed design method carries with it three sets of advantages. First, there are advantages in the systematic evaluation of the different alternative designs with respect to a set of criteria. The final design and future plant operation are greatly influenced by environmental, social, economical, and technical aspects. These should be taken into account as early as possible and in a systematic fashion in the design process.

Second, advantages are derived from the seamless integration of simulation (through GPS-X) into the evaluation of the different alternative designs. Integrating a simulator in the decision process allowed us to adjust the parameters of the operation and approach an optimum choice for each of the decisions.

Finally, there are advantages in the maintenance of a record of the design process achieved with DRAMA. Keeping a record of the design process improves communication and coordination both among design participants and with others, such as present and future inspectors. Furthermore, future redesign is made easier in the event that changes in operation become necessary due to changes in legislation (e.g., changes to permitted limits of BOD_5, COD, TN, etc.), in technology (e.g., new types of reactors or new treatments), or simply in plant capacity (e.g., increased population).

Nomenclature

BOD_5 = biochemical oxygen demand (g m^{-3})
COD = chemical oxygen demand (g m^{-3})
SS = suspended solids (g m^{-3})
TKN = total kjeldahl nitrogen (g m^{-3})
TN = total nitrogen (g m^{-3})
MLSS = mixed liquor suspended solids (g m^{-3})
MLVSS = mixed liquor volatile suspended solids (g m^{-3})

Acknowledgment

The authors acknowledge the cooperation of the group of experts in the field of WWTP design and operation, and especially Angel Freixó (responsible of the Granollers WWTP). This work has been supported by the Spanish MCyT project DPI-0665-C02-01. N.V. acknowledges a predoctoral TDOC grant.

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Received for review August 1, 2001
Accepted June 27, 2002

IE010652B