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Optimum Design of Activated Sludge Plants using the Simulator Daisy 2.0

A. Rivas & E. Ayesa
Section of Environmental Engineering, Centro de Estudios e Investigaciones Tecnicas de Guipuzcoa CEIT P° Manuel Lardizabal 15 Apd 1555, 20009 San Sebastian, Spain. Email: arivas@ceit.es

Abstract

This paper presents the theoretical basis and some practical applications of the simulation program **DAISY** (Activated Sludge **DY**namic sImulator) version 2.0 with the aim of optimizing the design of complex activated sludge plants for wastewater treatment. The software, developed by CEIT, was designed for the Spanish firm CADAGUA S.A. and is currently used as design tool by the engineering department of the company.

The new version of the simulator introduces an optimization module that estimates automatically the optimum dimensions and of an activated sludge plant to reduce the global cost function that could include effluent quality, construction cost and plant restrictions. This global cost function can combine continuous cost and penalty functions.

The automatic optimization is based on a direct search algorithm introduced in the simulation software previously developed. This algorithm determines the path towards an optimum by evaluating the objective function at several points without calculating derivatives.

The paper includes some examples to illustrate the vast possibilities of these kind of optimization procedures in the design of complex wastewater treatment plants including organic matter and nutrient removal.

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1 Introduction

The quality required in the effluent of the wastewater treatment plants (WWTP) has been increased during these last years. New requirements for nitrogen and phosphorous removal have generated a new generation of WWTP with complex configurations including oxic, anoxic and anaerobic reactors and internal recycles. This kind of new plants can not be designed based on classical criteria and the use of simulation programs for WWTP design and dimensioning are widely introduced in the engineering companies.

However, when the complexity of process configuration and the number of parameters to be selected increases, the selection of the most appropriate design parameters becomes a very difficult task, even for experienced people using simulation programs. The combined effects of each selected parameter and the existence of multiple objectives and limitations (quality of the effluent, safety, robustness, building costs, physical constraints, etc.) generates a huge number of possibilities to check and compare.

For this reason, the application of optimization algorithms to conventional simulation programs for WWTP design, can facilitate the selection of the appropriate design parameters. Adequate balance of every cost and objetive in a global "cost function" is crucial for the validity of results. From this "global cost function" that must include effluent requirements, cost functions and possible constrains, the optimization algorithm must be able to estimate automatically the "optimum" dimensions of the plant in the sense of "minimum cost".

2 Mathematical background

The global cost function to be optimized by the optimization procedure could include in its most general formulation real building costs and constraints.

The real costs are functions of the numerical value of a set of process variables. Some of these variables, called independent variables, can be externally fixed by the designer (ie.: volumes, dissolved oxygen concentration, etc.) The other variables, called dependent variables, are results obtained from predictions of the mathematical model of the plant (concentration of pollutants in the effluent, sludge productions, oxygen requirements, etc.)

The relationship between both kinds of variables is not functional or analytical, because the evaluation of the dependent variables needs a previous numerical resolution of the steady state of the plant. An algorithm based on the Newton-Raphson method has been implemented for this purpose [1].

The constraints are frequently associated with effluent requirements (maximum concentration of pollutants) or physical restrictions of the problem and could be converted to penalty functions.

So the global cost function can be expressed as,

$$C(\alpha_1,\cdots,\alpha_n)=\sum_{i=1}^{n}C_{\alpha,i}(\alpha_i)+\sum_{j=1}^{m}C_{\beta,j}(\beta_j)+\sum_{k=1}^{p}C_{R,k}(\alpha_1,\cdots,\alpha_n,\beta_1,\cdots,\beta_m) \quad (1)$$

Where:

$C(\alpha_1,\ldots,\alpha_n)$ is the global cost function.

$C_{\alpha,i}(\alpha_i)$ is the cost associated to the i-th independent variable.

$C_{\beta,j}(\beta_j)$ is the cost associated to the j-th dependent variable.

$C_{R,k}(\alpha_1,\cdots,\alpha_n,\beta_1,\cdots,\beta_m)$ is the cost associated to the k-th restriction, expressed as penalty function.

2.2 Optimization method

Many methods exist in mathematical programming to resolve the problem of maximization or minimization of a function under certain constraints. Every method has followers and detractors according to the results obtained in specific cases. Certain methods are more useful than others to optimize the design of activated sludge plants.

Optimization analytic methods based on differential calculus are not applicable to the problem because the cost and constraints have no functional or analytical relationship with the independent variables.

Linear, geometric and quadratic programming have been used in this kind of problem [2]. These methods need the cost function and the constraints are expressed in a particular form of the independent variables. It makes necessary to rewrite the plant model losing the general application and the prediction efficiency of the complex model.

Two large groups of methods are direct search and gradient. These offer more possibilities for application in the design of activated sludge process.

Gradient methods are based on the property of the gradient vector which is the greatest direction of increase or decrease. In these methods it is necessary to evaluate the function cost as well as its derivatives. To evaluate numerically the derivatives means increasing the number of function cost evaluations and so the computational effort.

Direct search methods determine the path towards the optimum according to a certain strategy by evaluating the objective function at several points and, therefore, a new set of independent variable values at each step will calculated.

Daisy's 2.0 optimization module works with a direct search method based on Pattern Search method [3] with some changes in relation to its original form. Figure 1 and 2 show graphically the bases of the algorithm for a simple two-dimensional case $C(\alpha_1, \alpha_2)$. The selection of this particular case does not decrease the generality.

The method begins by selecting a point of independent variables space $A_i=\{\alpha_1^i, \alpha_2^i\}$ and assigning to each variable α_j an incremental value ε_j (j=1,2).

The cost function is evaluated around A_i as Figure 1 shows. 3^n-1 A_{ij}^* points are obtained in this exploration. The least cost point of A_{ij}^* (for example A_{ik}^*, k=8) is compared with A_i so that if $C(A_{ik}^*)<C(A_i)$ a set of variable independent values are found that provide a least global cost.

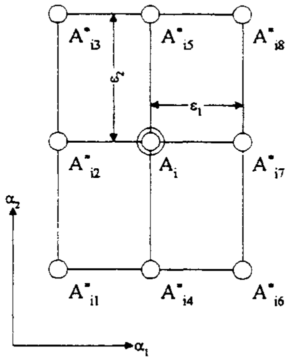

Figure 1. Explorations Points

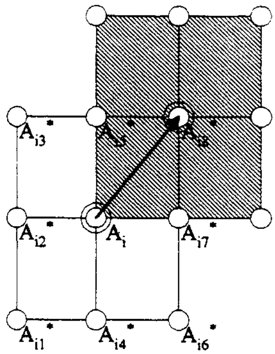

Figure 2. Improvement movement

The method continues with a movement towards point A_{ik}^* (Figure 2). This point A_{ik}^* carries out in the next iteration i+1 the role of A_{ij}^* and the process is repeated.

When in the i-th iteration, the exploration around A_i does not cause a A_{ij}^* that fulfills $C(A_{ij}^*)<C(A_i)$ so no point exists around A_i, with the actual search steps, which yields a better cost function value. When this happens, the search area is modified so $\alpha_j^i - \varepsilon_j < \alpha_j < \alpha_j^i + \varepsilon_j$, the search steps are reduced by a constant factor and a new exploration around A_i begins again. The method finishes when the search steps have been reduced to certain preassigned minimal values. This indicates that an optimum has been found.

The method has been implementated in Daisy 2.0 as explained above. This first implementation has been useful to check if the method and results were correct.

3 Daisy 2.0 simulator

Daisy 2.0 is a new version of Daisy, activated sludge plants simulator program developed in the Environmental Engineering Section of CEIT for the Spanish firm Cadagua S.A. The new version of the simulator contained, in addition to the three main modules: Design, Dynamic Simulation and Steady State module already contained in the first version [1], the Optimization module. The program also presents a new and more friendly user interface (Figure 3).

Like the first version the plant configuration, components and hydraulics unions can built with the Design module. The dynamic response of the plant and its steady state point are calculated with the Dynamic Simulation and the Steady State module respectively.

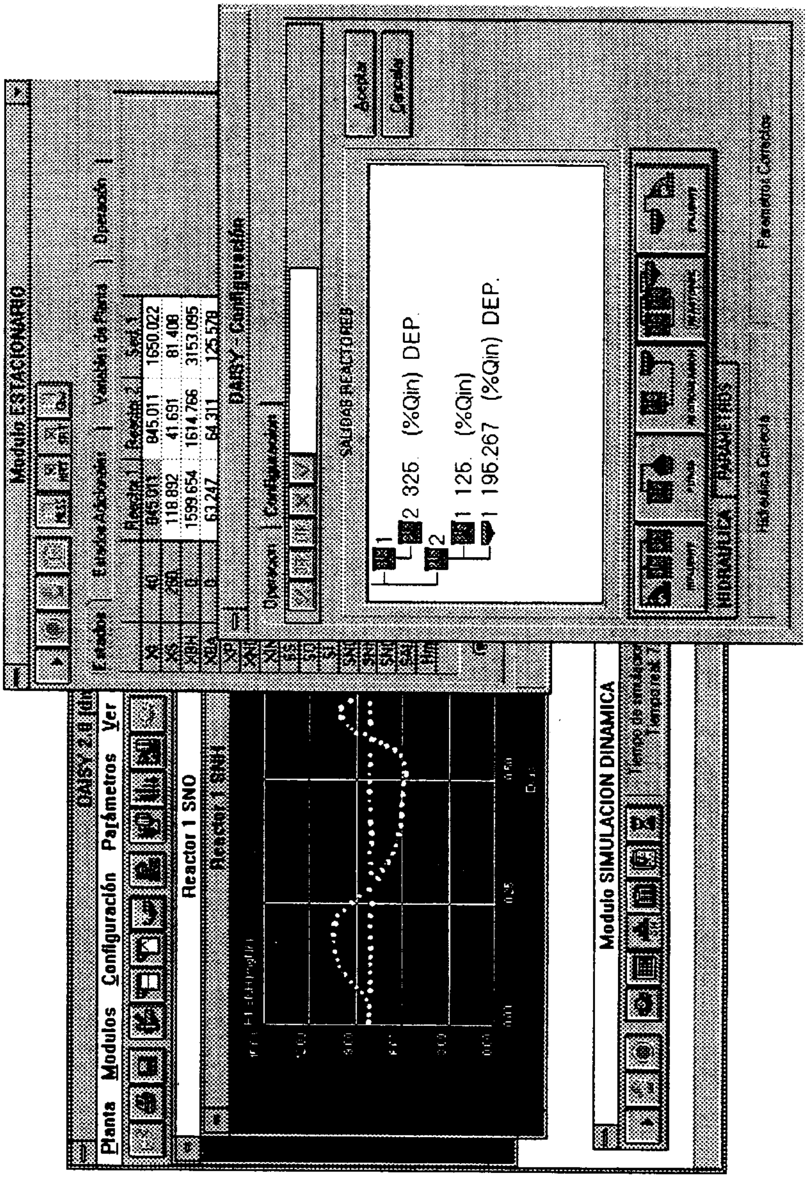

Figure 3 New User Interface of Daisy 2.0

3.1 Optimization Module.

The optimization module is totally integrated in the Daisy simulator. It works together the Dynamic Simulation and Steady State module on the design of plants. The optimization module combines the steady state point calculation, the cost evaluation and the early mentioned optimization method (Figure 4).

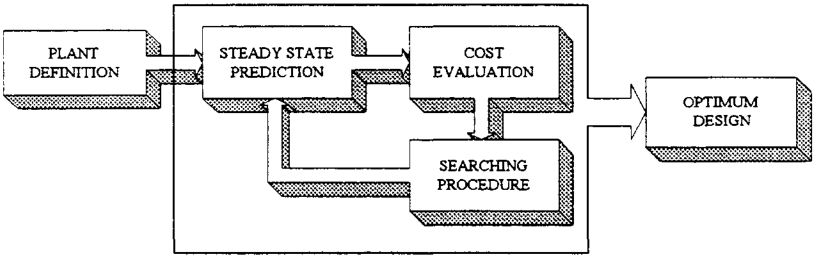

Figure 4. Optimization Algorithm.

The module allows optimization of at most nine independent variables from a given plant configuration. Generally it is possible to select:

- Solid Retention Time (SRT).
- The volume fractions of reactors (both individual reactor and plug flow reactor).
- The fractions of influent flow.
- Internal Recycles.

It is necessary to fix a search step and a search domain for each kind of independent variables and for each variable respectively. This domain is determined by both maximum and minumum variable value (Figure 5).

The selected constraints can be associated with effluent requirements, nitrate and ammonia nitrogen concentrations or total nitrogen (nitrate plus ammonia nitrogen) concentration. It can be related also to physical restrictions of the system as the solids concentration in the reactor before the settler. (Figure 5)

The user can select the kind of optimization that he desires. The program presents a refined optimization, a gross optimization and a SRT sweep optimization (Figure 5).

Once the all parameters are fixed and correct the optimization procedure can start. As the optimization procedure advances the program shows the user the successive sets of variables generated by the algorithm in its hunt towards a minimum

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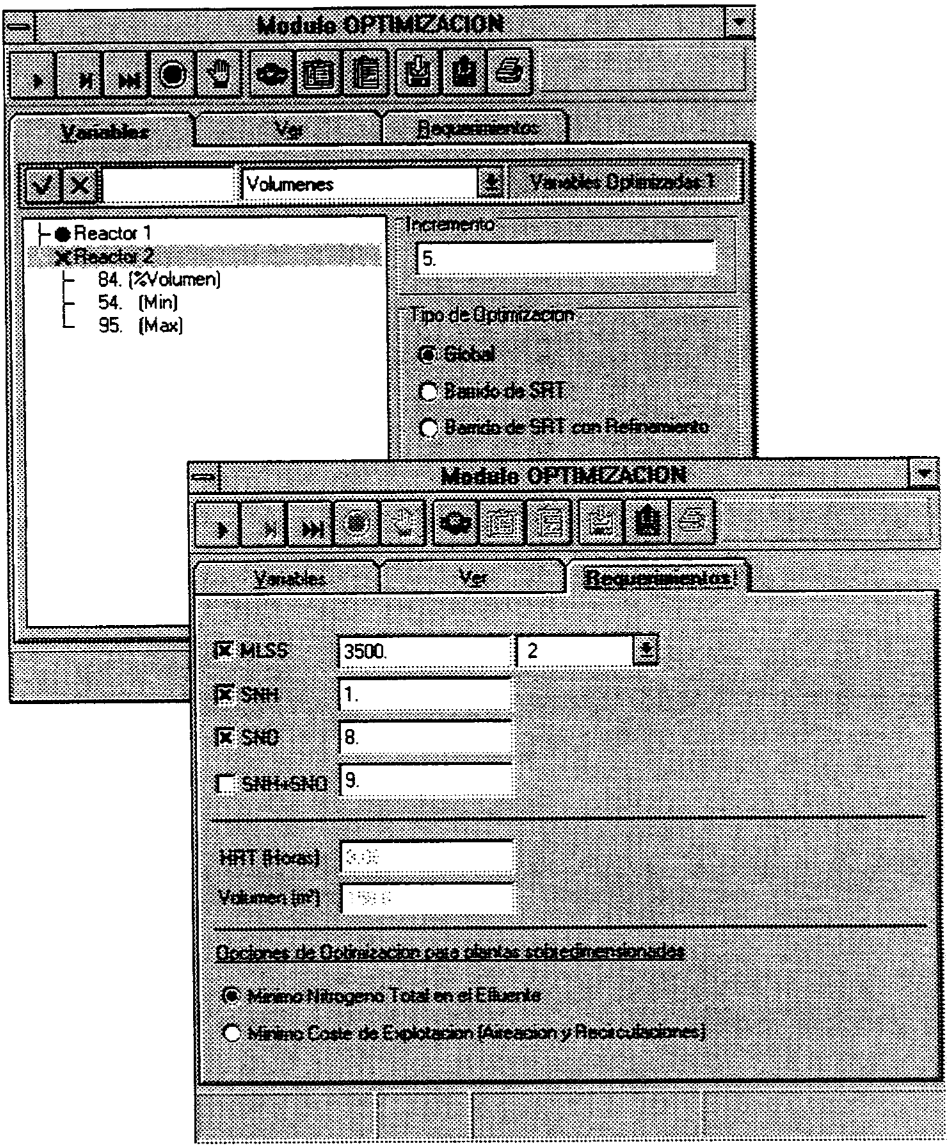

Figure 5. Optimization Module. Optimization Parameters and Requeriments

4 Optimum design with Daisy 2.0.

As an example of possibilities of the software a DN process (Figure 6) has been designed using the optimization module of Daisy. The DN is a treatment for organic matter and nitrogen removal. This plant includes two reactors, one anoxic reactor (D reactor) and one oxic reactor (N reactor). The influent feed, internal recycle and sludge recycle are introduced to the anoxic area.

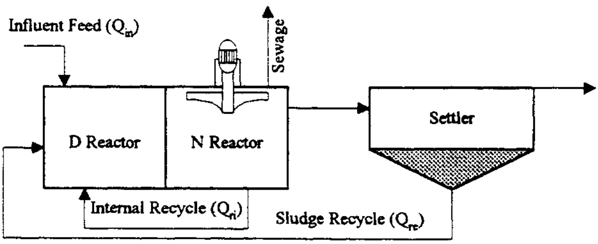

Figure 6. DN Process

The characteristics of the influent wastewater are those typically found in urban wastewater and the numerical values of model parameters are the commonly used by the bibliography. The temperature of the plant is 13° C and the concentration of dissolved oxygen in N reactors is controlled to 2.0 mg/l.

The design restrictions in this particular example are:

- Ammonia concentration in the N reactor ≤ 1 mg/l
- Nitrates concentration in the N reactor ≤ 8 mg/l
- Suspended solids concentration in the N reactor ≤ 3500 mg/l

The set of design variables selected to be optimized are the solid retention time (SRT), the volume fractions of reactors and the internal recycle (Q_{ri}). In this example the initial values and search steps are shown in Table 1.

	Initial Values	Search Step
SRT (Dias)	5	1
Vol D (%)	50	1
Vol N (%)	50	1
Q_{Ri} (%Qin)	100	25

Table 1

The program was executed in a PC with a Intel 486 processor at 66 MHz., spending 8 minutes to reach a minimum. The program needed 28 iterations and 717 steady state point calculations to reach the optimum design. The optimization results are shown in Table 2.

Optimum design parameters	
SRT (Days)	20.6
Vol D Reactor (%)	45
Vol N Reactor (%)	55
Q_{ri} (%Qin)	160
HRT (Hours)	15.68
Requirement obtained	
Effluent Ammonia (mg N/l)	0.99
Effluent Nitrates(mgN/l)	7.99
Suspended solids in last reactor (mg/l)	3485

Table 2

Any other combination of design parameters will overcome the restrictions or will increase the required volume.

Local minima can be frequently observed and a systematic scan has been introduced to detect all the possible minima inside the range of design parameters previosuly defined.

5 Conclusions

The optimization algorithms can be adapted sucessfully to the current wastewater treatment plant simulation programs. Daisy 2.0 is a sample of a programme that includes a fully integrated optimization module.

The results obtained in some minutes by the optimization algorithm are similar to those obtained by experienced design engineers. When the complexity of the problem increases the selection of the most appropiate design parameters using conventional rules is a very arduous (or even impossible) task. However, the only limitation of this kind of optimization algorithms is the computing time.

All kind of cost curves and constraints can be combined in a "global cost function" specifically adapted to every particular problem.

The Daisy 2.0 simulator presents a design and analysis programme for complex wastewater plant configurations incorporating a very easy and friendly user interface

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