INTEGRATION OF WASTEWATER TREATMENT PLANT INVESTMENT AND OPERATING COSTS FOR SCENARIO ANALYSIS USING SIMULATION

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ABSTRACT

Biotim and Biomath recently started an ambitious R&D program aiming at the development of a new modelling and simulation tool, MoSS-CC (Model-based Simulation System for Cost Calculation), that supports a holistic economic evaluation of a WWTP over its life cycle. The use of dynamic simulation and the integration of variable operating costs in the assessment of scenarios will maximise the optimisation of the WWTP process design itself and minimise the total wastewater treatment cost (investment cost + fixed and variable operating costs). In addition, using dynamic simulation allows the investigation of the potential benefits achieved when implementing adequate control strategies. In this paper, the first developments of the MoSS-CC software are presented, i.e.:
1- the principle of the scenario analysis using the MoSS-CC software tool, roughly consisting in two interdependent phases: the design phase and the dynamic analysis phase;
2- the definition of an objective economic index derived from cost functions, including both capital and variable operating costs;
3- the features of the VPL (Virtual Product Life-cycle), the software concept underlying MoSS-CC which is currently being developed.
It is expected that by the end of this year a prototype of MoSS-CC will be available for internal use.

INTRODUCTION

During the design phase of a new wastewater treatment plant (WWTP) or when upgrading an existing facility, different process alternatives and operating strategies could be evaluated by calculating a cost index using commercially available software packages (McGhee *et al*. 1983; Spearing, 1987). However, actual cost indices are often restrictive since only investment or specific operating costs are considered. In addition, time-varying wastewater characteristics are not directly taken into account but rather through the application of large safety factors. Finally, the implementation of adequate control strategies such as real-time control is rarely investigated despite their potential benefits (Vanrolleghem *et al*., 1996; Ekster, 1998).
Moreover, Biotim and other process and project engineering contractors active in the field of (waste)water treatment, are proposing new contracts based on the BOOT (Built, Owned, Operated and Transferred) concept, for which the total (waste)water treatment cost, i.e. investment cost + fixed and variable operating cost, is of utmost importance.
Therefore, Biotim and Biomath started an ambitious R&D project aiming at the development of a new software tool, MoSS-CC (Model-based Simulation System for Cost Calculation) for the purpose of a holistic economic evaluation of a WWTP over its life cycle. MoSS-CC aims at the optimisation of a WWTP design and operation based on dynamic simulation and the integration of investment costs and fixed and variable operating costs.

In this paper, the principle of the scenario analysis implemented in MoSS-CC is illustrated. Secondly, an objective economic index, including both capital and variable operating costs over the life span of a WWTP, is defined. Finally, the software concept, called VPL (Virtual Product Life-cycle) (Vangheluwe *et al*. 1994), and its implementation are described.

PRINCIPLE OF SCENARIO ANALYSES IMPLEMENTED IN MOSS-CC

Figure 1 presents the principles of scenario analyses implemented in MoSS-CC.

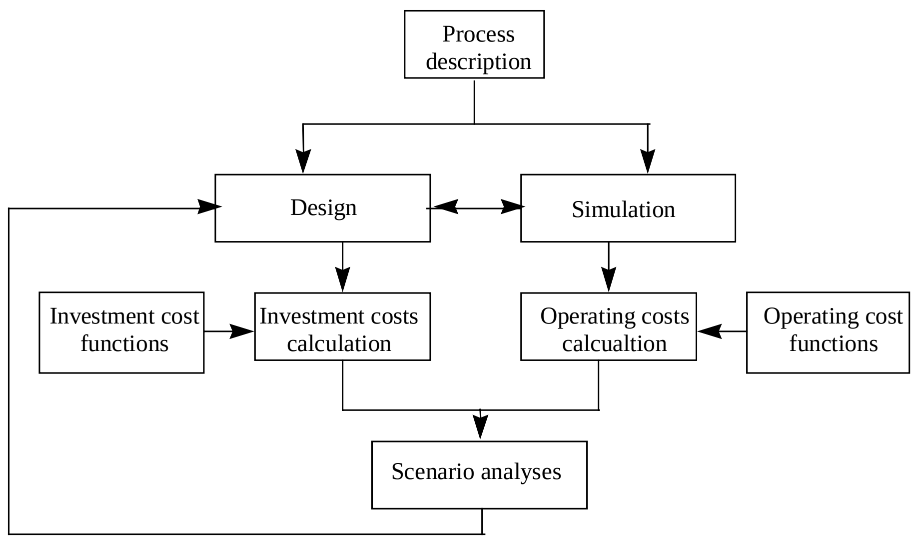

Figure 1. Principle of scenario analysis in MoSS-CC

As illustrated in Figure 1, to optimise a new plant or to upgrade an existing one with MoSS-CC, the evaluation of different possible alternatives should rely on the following aspects:

1. integration of the plant design procedure and the simulation of the plant's dynamic behaviour;
2. integration of the investment and operating costs to evaluate the different scenarios.

Starting from the limitations of current cost calculation practice, an automated and standardised procedure was to be established which aggregates investment, fixed and time-varying operating costs, in an objective cost index. In addition, a software tool that guides the user throughout the design procedure had to be developed. These aspects are further described in detail.

WASTEWATER TREATMENT PLANT COST INDEX

Within MoSS-CC, an objective cost index should integrate the investment cost as well as fixed and variable operating costs. The latter are usually not taken into account in commercially available software tools or optimisation studies according to literature (McGhee *et al.*, 1983; Tyteca, 1985; Spearing, 1987; Pipyn *et al.*, 1994; Fels *et al.*, 1997).
In order to assess the preliminary costs of a wastewater treatment plant - to be able to choose between different alternatives in the early phase of a process design - cost functions may be used (Wright and Woods, 1993 - 1994; Agences de l'eau, 1995; Fels *et al.*, 1997; Vermeire, 1999). Therefore, different investment and operating cost functions are presented in the sequel, which may guide the development of a systematic cost calculation procedure.

Investment cost functions

Investment costs for major treatment plant units may be quantified as a function of the process size (e.g. volume, area, flow rate) by use of power laws or polynomial functions. To estimate investment costs related to piping or electrical works, cost factors (percentage of the investment cost) are often applied. Examples of investment cost functions that may be found in the literature are presented in Table 1.

Table 1 – Examples of investment cost functions

Unit	Item	Cost function	Parameter	Parameter Range	Reference	Cost Unit
Influent pumping station	Concrete	$2334\ Q^{0,637}$	Q = flow rate (m^3/h)	250-4000	Vermeire, 1999	Euro of 1998
	Screws	$2123\ Q^{0,540}$				
	Screening	$3090\ Q^{0,349}$				
Any unit	excavation	$2.9\ (\pi/4D^2 H)$	D = diameter (m) H = height (m)	Not defined	Fels *et al.*, 1997	Can$ of 1995
	compaction	$24.1*0.4(\pi/4D^2)$				
	concrete base	$713.9*0.5(\pi/4D^2)$				
	concrete wall	$933.6*0.5\ \pi\ D\ H$				
Oxidation ditch	Concrete	$10304\ V^{0,477}$	V = volume (m^3)	1100-7700	Vermeire, 1999	Euro of 1998
	Electromech.*	$8590\ OC^{0,433}$	OC = oxygen capacity (kgO_2/h)	30-630		
Settler	Concrete	$2630\ A^{0,678}$	A = area (m^2)	175-1250	Vermeire, 1999	Euro of 1998
	Electromech.	$6338\ A^{0,325}$				
		$824\ I\ A^{0.77}$	A I = Engin. News Record index**	Not defined	Tyteca, 1985	US$ of 1971
	Concrete	$150(A/400)^{0.56}$ $150(A/400)^{1.45}$	A	60 – 400 400 – 800	Wright and Woods, 1993-1994	Can$* 1000 of 1990
	Electromech.	$60(A/220)^{0.62}$	A	60 - 7000		
Sludge pump	Electromech.	$9870\ I\ Q^{0.53}$	Q, I	Not defined	Tyteca, 1985	US$ of 1971
	Electromech.	$5038\ Q^{0,304}$	Q	35-2340	Vermeire, 1999	Euro of 1998

* Electromech. = electromechanical equipment

** Engineering News Record index = index used to update costs in United States

On the basis of functions such as presented in Table 1, the investment cost of a wastewater treatment plant may be calculated. However, when only using literature data, accurate estimation of investment costs can hardly be expected. Cost functions are indeed developed at a given time for a specific company, region or country and any extrapolation is not without risk. Moreover it is difficult to compare various relationships extracted from different sources, as the description of the components taken into account in the relationships is often poor, and an indication of the accuracy obtained using literature data is rarely provided. As a result, cost analysis in the early phase of a process design requires the development of specific cost functions, to obtain an accurate and reliable cost estimation.

Operating cost functions

The total operating cost of a WWTP may be related to global plant parameters (e.g. average flow rate, population equivalent), generally through power laws (Smeers and Tyteca, 1984; Balmér and Mattson, 1994; WERF, 1997). However, such relationships apply to the average performance of plants and often suffer from a high uncertainty, unless very similar plant configurations are considered.

In order to take into account dynamic simulation data to estimate operating costs, deductive models may be issued from engineering calculations (Brett *et al*., 1998; Jacquet, 1999). However, such development requires some skill, and on-site data collection is preferable when possible (e.g. for an upgrade of an existing plant), in order to check and refine existing cost models or to build new (inductive) models on the basis of collected data. Table 2 and 3 compile different cost functions that may be used to estimate fixed and variable operating costs.

Table 2 - Examples of fixed operating cost functions

Cost item	Cost function			Reference
	Formula	Symbols	Units	
Normal operation and maintenance	L = Uc PE	L = labour Uc = unit cost PE = population equivalent	man-hour/y man-hour/y/PE -	Jacquet, 1999
Clarifier mechanism	$P = \theta A^b$	P = power θ, b = constant A = area	kW - m^2	Fels *et al*., 1997
Mixers	P = Ps.V	P = power Ps = specific power V = volume	kW kW/m^3 m^3	Jacquet, 1999
Small equipment (supplies, spare parts…)	C = Uc.PE	C = cost Uc = unit cost PE = population equivalent	Euro/y Euro/y/PE -	Alexandre and Grand d'Esnon, 1998
Analyses	C = Uc.PE	C = cost Uc = unit cost PE = population equivalent	Euro/y Euro/y/PE -	

Table 3 - Example of variable operating cost functions

Cost item	Cost function			Reference
	Formula	Symbols	Units	
Pumping power	$P = Qwh / \eta$	Q = flow rate P = power w = specific liquid weight h = dynamic head η = pump efficiency	m^3/s kW N/m^3 m -	ASCE, 1992
Aeration power (Fine bubble aeration)	$q_{air} = f(K_L a_f)$ $P = f(q_{air})$	q_{air} = air flow rate P = power $K_L a_f$ = oxygen transfer coefficient in field conditions	Nm^3/h kW 1/h	Jacquet, 1999 Gillot *et al*., 1999
Sludge thickening dewatering and disposal	C = Uc TSS	C = cost Uc = Unit cost TSS = excess sludge	Euro/y Euro/t TSS t	Alexandre and Grand d'Esnon, 1998
Chemicals Consumption	C = Uc Cn	C = cost Uc = unit cost Cn = consumption	Euro/y Euro/kg kg	
Effluent taxes (organic matter and nutrient)	$L = Uc * (k_{org}.N_{org}+k_{nut}.N_{nut})$	Uc = Unit cost N_{org} = f(Q, BOD, TSS, COD) N_{nut} = f(Q, N, P)	Euro/unit	Vanrolleghem *et al*., 1996

Cost functions given in Tables 2 and 3 only illustrate possible models in their generic form. As seen in Table 2, fixed operating costs may be related to the plant size or unit size (PE, volume, area). The assessment of variable operating costs on the basis of simulation variables and parameters requires a number of hypotheses (e.g. head losses, oxygenation efficiency, see Table 3): each particular case may thus require the development of specific cost functions.

Finally, when comparing different alternatives, special attention should be paid to the time and space scales chosen (Vanrolleghem *et al.*, 1996), as they may influence the choice of the implemented cost functions (Rivas and Ayesa, 1997). At best, an overall plant evaluation over the life span of the plant should be conducted.

Total cost of a WWTP

The total cost of a plant is usually determined using the present worth method (White *et al.*, 1989). All annual operating costs for each process are converted into their corresponding present value and added to the investment cost of each process to yield the net present value (NPV). When IC_k represents the investment cost of a unit k, and OC_k the operating cost, the net present value of a plant over a period of n years can be determined as:

$$NPV = \sum_{k=1}^{N} IC_k + \left(\frac{1-(1+i)^{-n}}{i} \right) \sum_{k=1}^{N} OC_k \quad (1)$$

Where i is the interest rate and N is the number of units.
Results could also be expressed as equivalent annual worth (AW):

$$AW = \frac{i(1+i)^n}{(1+i)^n - 1} \sum_{k=1}^{N} IC_k + \sum_{k=1}^{N} OC_k \quad (2)$$

On the basis of functions, such as presented in Tables 2, 3 and 4, an overall cost index may be formulated as the NPV or the AW.

MOSS-CC DESIGN PROCEDURE

In Figure 2, the procedure underlying MoSS-CC and its software implementation are depicted.

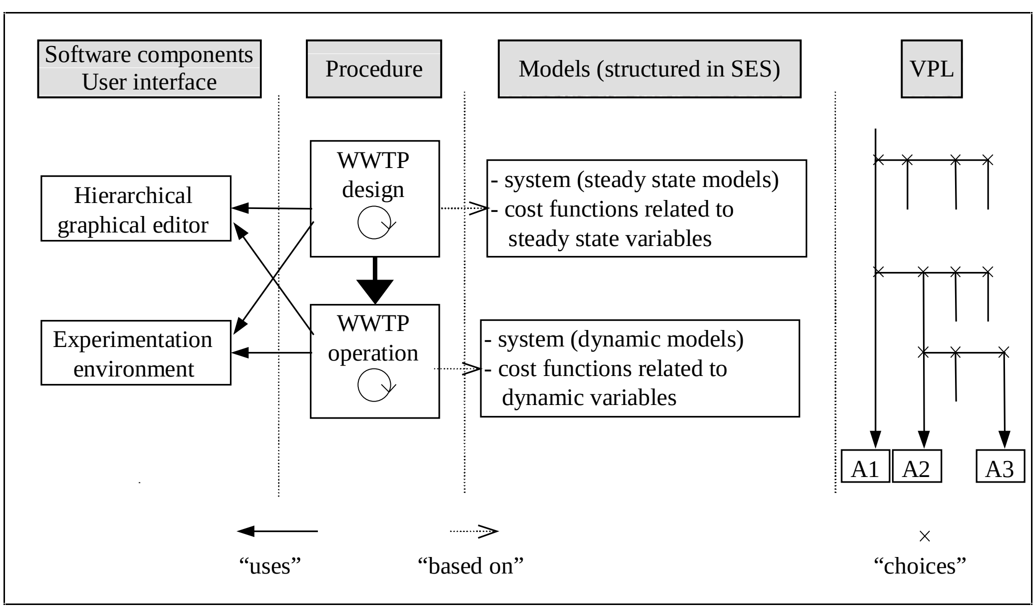

Figure 2. MoSS-CC design procedure

The procedure is following the Virtual Product Life-cycle (VPL) paradigm (Vangheluwe *et al*., 1994) as it describes (and partially prescribes) the evolution of the system-to-be-designed ("virtual", as all experiments are conducted through simulation). It consists of two major phases:

1. the design phase, during which structural decisions are made (*i.e*., the different process units are chosen). Mostly, given an average "design" input (the wastewater to be treated) and desired output for the system to be built (effluent quality, sludge production), steady-state models are used to determine structural parameters (such as reactor volumes, surface of settling tanks, pump and blower capacities, ...). Only investment and fixed operating costs are considered;
2. the dynamic analysis phase, where behavioural choices are made (optimal selection of operating conditions, controller tuning, ...). Variable operating costs are added.

At the core of MoSS-CC is the realisation that both system behaviour and cost are explicitly represented in the form of models.

The cycle in both phases, design and operation (see Figure 2), denotes an iterative process for which simulation support is given by the WEST® (Hemmis, Kortrijk, Belgium) interactive modelling and simulation environment (Vangheluwe *et al.,* 1998).

In both cycles, the process iterates over:
1. interactively building a model by connecting basic building blocks representing the WWTP's units (with the hierarchical graphical editor, cf. Figure 2);
2. simulation, e.g. determining the expected effluent quality, investment and operation costs, etc. through experimentation with the model;
3. either the process stops here or further refinement is needed. In case of refinement, the model, augmented with the simulation results obtained for particular parameter settings and conditions, allows one to choose between a number of alternatives for each of the sub-models.

In the design phase, a choice has to be made between alternative structural choices. In the dynamic analysis phase, one typically chooses from different levels of process detail (*e.g*., IAWQ Activated Sludge Model 1 or 2, point settler or Takacs settler model). A System Entity Structure (SES) (Zeigler, 1984), a tree-shaped knowledge structure that maximises model reuse, provides the choice space for the user. In essence, the SES encodes design and modelling knowledge. In MoSS-CC, the process deign standards of Biotim have been implemented as design models and the WEST® wastewater treatment modelbase is used for dynamic simulation.

Finally, in the VPL tree (see figure 2), the MoSS-CC environment keeps track of all choices made during the decision process described above. This allows the user, by means of a VPL browser, to trace back to any previous choice and to try other alternatives. Thus, arbitrary feedback is added to the process and scenario analysis, whereby it becomes possible to compare consequences (A1, A2, A3 in Figure 1) of different choices made during the process.

CONCLUSION AND PERSPECTIVES

This paper introduced the concept of MoSS-CC, a modelling and simulation tool aiming at integrating the calculation of investment and fixed and variable operating costs of a WWTP. The integration of variable operating costs in the assessment of scenarios allows to refine the cost analyses and to quantify the impact of real time control. In addition, MoSS-CC is based on a standardised calculation procedure, and thus allows to avoid the major shortcomings of the actual cost evaluation methodology, which have been highlighted in this paper.

The principle of scenario analyses implemented in MoSS-CC has been presented. Subsequently, an objective economic index was given. This index is derived from cost functions, including both capital and variable operating costs over the life span of a WWTP and should be further refined before being implemented in the software. Finally, the VPL procedure and its software implementation have been described.
Biotim and Biomath are currently developing with united efforts the so-called MoSS-CC software tool. It is expected that by the end of this year a prototype of the software will be available for internal use. This prototype will then be tested during the design phase of several new WWTP's and/or the upgrading of existing plants.

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