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MULTI-OBJECTIVE CONTROL OF URBAN WASTEWATER SYSTEMS

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Abstract: This paper discusses the development of control algorithms for the urban wastewater system. This system is considered to comprise of sewer system, wastewater treatment plant and receiving watercourse. Since control actions are affecting the water quality in the river, river water quality based objectives, rather than conventional criteria such as overflow volumes or loads, are applied in this study when determining the optimum control algorithm. The aim of achieving optimum performance of the urban wastewater system with regard to oxygen and ammonium concentrations in the river defines an optimisation problem with multiple objectives, which is solved by application of an evolutionary algorithm and by calling the urban wastewater system simulator SYNOPSIS as a means to evaluate the objective function. Application to control of a semi-hypothetical case study demonstrates the benefits of this technique and encourages further studies in this unique application area. *Copyright © 2002 IFAC*

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1 INTRODUCTION

Urban wastewater systems, consisting of sewer system, wastewater treatment plant and a receiving water body, have been planned, designed and operated for some time. Figure 1 provides an overview over the most relevant elements of the wastewater system and the water flows involved. The primary objective of such systems is to dispose of wastewater in a hygienic way. Additional objectives usually include the avoidance of flooding, the minimisation of the detrimental effects on the environment and the minimisation of capital expenditure and operational costs.

Wastewater from private households as well as from industry are collected in sewer systems and are, in case of combined sewer systems, mixed with surface runoff, caused by rainfall water falling on the surface of the catchment. The wastewater is then conveyed towards the wastewater treatment plant. Any flows exceeding the capacity of the sewer system are discharged (essentially untreated) over overflow structures into a receiving water body, thus giving rise to water pollution. In order to cope with the varying flows through the sewer system, many sewer systems also contain a number of storage tanks or storage pipes, providing capacity for temporary storage of wastewater. Wastewaters arriving at the treatment plant is treated with an efficiency strongly dependent on the design and the status of the plant and the flow and load characteristics of the inflowing wastewater. Finally, treated wastewater is led into a receiving water body. In most systems, overflows from the sewer system and treatment plant effluents are discharged into the same watercourse.

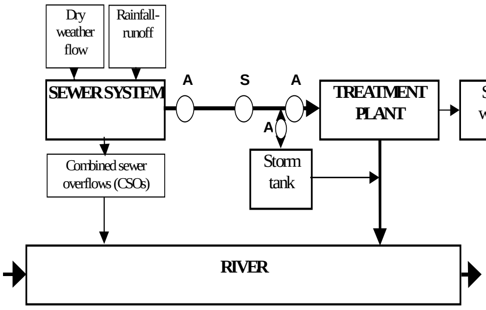

Figure 1: Schematic overview of an urban wastewater system with actors (“A”) and sensors (“S”) as discussed in Section 6

2 CONTROL OBJECTIVES

For the design of control algorithms, criteria have to be defined which enable an evaluation and a comparison of different algorithms. In traditional operational practice for sewer systems, often criteria such as overflow volume or pollutant load discharged are applied. Such auxiliary criteria, however, have been shown, to correspond only poorly with water quality in the receiving water course (Rauch and Harremoës, 1996; Butler and Schütze, submitted). Treatment plant operation often aims at maintaining limits of effluent concentrations and the reduction of operating costs. For assessing the impacts of urban pollution discharges on aquatic life in the river, not only hydraulic effects and pollutant discharges are of relevance, but also the upstream conditions (e.g. the river’s dilution capacity) as well as the boundary conditions for transformation processes in the river are of importance. Even from this short overview, it becomes obvious that the operation of urban wastewater systems requires a multitude of objectives to be considered.

Whilst some approaches to optimisation with regard to several objectives have been reported, e.g. for treatment plants (Jumar and To, 2001), the use of multiple-objective optimisation procedures for the entire wastewater system has hardly been reported yet. The work by Rauch and Harremoës (1999), outlining the problem, represents a notable exception. Traditional approaches focus on consideration of just a single objective. This may be composed of several objectives by weighing (involving uncertain weighing factors).

In order to enable several objectives to be taken into account simultaneously, this paper outlines a procedure for the control of urban wastewater systems which is based on the consideration of multiple criteria describing water quality in the river (and thus the performance of the urban wastewater system adequately).

As the two most crucial parameters for the description of urban impacts on river water quality, dissolved oxygen and ammonium-ammonia concentrations have been identified in a number of studies (cf. also the Danish guidelines for the design of wastewater systems as well as the British “Urban Pollution Management Manual” (FWR, 1994, 1998)).

Assuming that the control algorithm for a given urban wastewater system can be completely described by a set of if-then rules and/or by a number of controllers as known from control theory, it is possible to describe the control algorithm by a finite number of numerical parameters. Consequently, the task of finding a good (or even, in some sense, optimum) control algorithm consists of two parts: Firstly, the framework of the controllers and control rules has to be set up. For example, it has to be specified which control input is to be operated in dependence of which sensor information is specified. At this stage, the experience of the system designer or operator can be incorporated into the control algorithm. The second stage consists of assigning numerical values to the parameters of the controllers - a tedious task which can be aided significantly by the use of optimisation techniques.

A formalisation of this procedure is easily possible: Assuming that the control framework (set of controllers and rules without values for its parameters) is given, the control algorithm is defined by a (finite) number of n parameters. Application of this control algorithm will result in the urban wastewater system having a certain performance over a given time period (e.g. an individual rainfall event or a long time series). Such performance can be expressed by various criteria, ranging, for example, from total overflow volumes to pollutant loads to receiving water quality based criteria. Costs (capital and operational) also could be considered here. The value of such criteria can be either a scalar (m = 1) or a vector (m > 1), with the latter option resulting in a multicriterial problem definition. Once an appropriate simulation tool is available, the processes, and thus the behaviour of the system under various strategies as input can be simulated. The problem to find a good (or optimum) control algorithm is now reduced to the problem of determining those values for the control parameters (a_i, i=1,..,n) which result in good values of the performance measure $f(\underline{a}) \in \Re^m$ (see Figure 2).

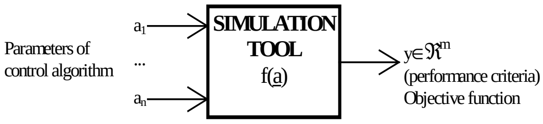

Figure 2: The role of the simulation tool as a means to evaluate the objective function

The approach chosen here ("off-line optimisation") differs from the concept of "on-line optimisation", which solves at every control time step an optimisation problem in order to determine the best control action to be taken. Such an approach requires a system description of the urban wastewater system and the related processes, which has to be, on one hand, sufficiently detailed so as to allow a realistic analysis of the system and its behaviour. On the other hand, however, the system description has to be simple enough to allow for a large number of different control scenarios to be analysed and compared with each other, during run time, at every control time step. In order to achieve this, often a significant simplification of the system description proves to be necessary. In particular when considering not only individual elements of the urban wastewater system, but the wastewater system in its entirety (as is done here) and when considering water flow and quality processes, which potentially have effects over long time periods (e.g. loss of nitrification within the treatment plant; sediment oxygen demand in the receiving water body), the on-line control approach appears to have a number of problems related to its practical applicability for the entire urban wastewater system.

Therefore, in this paper the aforementioned off-line approach is pursued and discussed further. The subsequent sections define the underlying objective problem. Then the simulation tool SYNOPSIS, which serves for the evaluation of the objective function, is briefly introduced before the optimisation procedures are demonstrated on an example.

3 THE OPTIMISATION PROBLEM

The optimisation problem can now be formulated as follows: the vector $\underline{a} \in \Re^n$ of the parameters of the control algorithm is mapped on a value of the performance criterion ($y \in \Re^m$). The task to determine those parameters of the control algorithm which (without loss of generality) minimise the value of the performance criteria is formulated in Equation 1. Minimisation of a vector is understood here as minimisation component-wise.

$$f(\underline{a}) = \min_{\underline{a} \in X}! \qquad (1)$$

where:

$\underline{a} \in \Re^n$: Parameters of the control algorithm

f: $\Re^n \rightarrow \Re^m$ function, having the parameters of the control algorithm as argument; this function is evaluated by application of the simulation model for a given input, utilising the performance criteria defined

Any constraints on the parameters of the control algorithm (such as upper/lower limits; non-negativity conditions etc.) can be included in the definition of the feasible set $X \subseteq \Re^n$, which may be continuous or discrete.

Equation (1) expresses this optimisation problem in a general way. It should be noted that no assumption is made on the properties of the objective function f (e.g. as to whether f is a continuous or even a differentiable function). Even in the single-criterion case (i.e., m = 1), no statement can be made about the unicity of the solution, i.e., the problem of local optima not being global ones may occur, thus making the use of gradient-based optimisation procedures doubtful.

In the present study, the simulated system is represented by the urban wastewater system and its related water flow and quality processes. Therefore, the definition of the objective function f is of complex nature, i.e. f can be described in an appropriate way only by a simulation model. A simplified representation of the objective function, as pursued for example in several studies on optimisation of real time control of flows in sewer systems only (e.g. linearisation, as for example in Schilling *et al.*, 1996), does not appear to be feasible when the urban wastewater system is to be considered in its entirety.

4 EVALUATING THE OBJECTIVE FUNCTION: THE MODELLING TOOL

For the model-based development of control algorithms for a given system, a model describing the relevant processes needs to be available. For the present task, the model SYNOPSIS ("Software package for synchronous optimisation and simulation of the urban wastewater system") as described by Schütze *et al.*, 1999, 2002a) is used. SYNOPSIS has been specifically designed for the application of optimisation routines for the development of control strategies of the urban wastewater system.

The simulator consists of submodules simulating water flow and pollution transport in the sewer system, treatment processes at the treatment plant as well as flow and water quality in rivers.

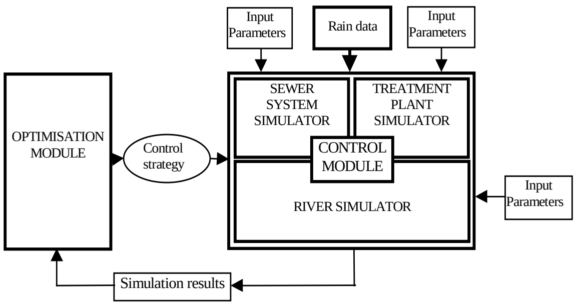

Figure 3: SYNOPSIS - a simulator for urban wastewater systems

The sewer system model is based on the KOSIM package (itwh, 1995), which models rainfall-runoff processes by application of the limit-value method, and flow on the catchment surface and within the sewer system based on the hydrological concept of reservoir cascades. Pollutant transport is modelled by translation, whilst sedimentation and conversion processes in the sewer system are not modelled in detail. The treatment plant model employed consists of dynamic submodules for primary and secondary clarifiers and of the aeration tank. Dynamic modelling of the activated sludge process follows the Activated Sludge Model No. 1 (Henze *et al.*, 1987). The river module uses the DUFLOW package (IHE, 1992): It simulates flow and pollutant transport in the river by solving the full Saint Venant equations and the Advection-Dispersion equation. A number of pollutant conversion processes (e.g., reaeration, decay of organic matter, nitrification, photosynthesis) is modelled by solving the appropriate user-defined differential equations.

Previous applications of SYNOPSIS were concerned with optimisation of just a single variable. Figure 3 presents an overview of SYNOPSIS and its interfaces to the optimisation procedure. The simulation model serves as a means for evaluation of the objective function as has been described in the previous section.

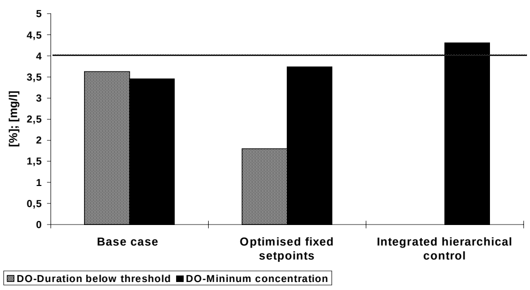

Figure 4: Comparison of various control scenarios with regard to oxygen balance only

Figure 4 illustrates the results of a simulation study (Schütze *et al.*, 1999; Butler and Schütze, submitted) using SYNOPSIS as a means to develop and to optimise a number of control algorithms of varying complexity. It can clearly be seen that integrated control can indeed improve the performance of the urban wastewater system, at least with regard to the oxygen balance in the river.

Even for a simple control scenario of optimised setpoints in the system (corresponding to the example discussed in the subsequent section), some considerable improvement in performance can be achieved (Schütze et al., 2002b). However, the question arises whether performance improvement is also possible with regard to several (potentially contradictory) criteria, such as oxygen and ammonium balances, at the same time. This again motivates the application of multi-objective optimisation techniques in wastewater management.

5 THE OPTIMISATION PROCEDURE

In order to solve the multi-criteria optimisation problem, an appropriate optimisation algorithm needs to be chosen. A number of routines are known in the literature (Cieniawski *et al.*, 1995; Gupta, 1999). Among the global optimisation procedures, which do not make assumptions on continuity of the objective function and which do not require information on its derivatives are the Evolution Strategies (To, 1997, 1999). This class of algorithms is related to the well-known category of genetic algorithms. The Evolution Strategies are also particularly suited for multi-objective optimisation since they allow the determination of the Pareto set of the solutions. Furthermore, they allow the consideration of linear and nonlinear constraints within the optimisation process. Through interface routines, these routines are used for solving the optimisation problem calling the simulator SYNOPSIS as the objective function.

6 AN APPLICATION EXAMPLE

The following example illustrates the application of the concepts described above. For a given semi-hypothetical urban wastewater system, a control algorithm for real time control is to be tuned.

The case study comprises of sewer system, treatment plant and receiving water body, structured as shown in Figure 1. A detailed description of the case study is given by Schütze et al. (2002a). The sewer system has four combined sewer overflows with on-line storage tanks associated with them. The outflow of these tanks can be controlled. The treatment plant (resembling the treatment works in

Norwich–Whitlingham, UK) is a conventional nitrifying activated sludge plant designed for a population equivalent of 150000. The storm tank at the works inlet can be used to temporarily store flows exceeding the capacity of the plant. All discharges are led into a river, which is characterised by a (dry weather) dilution ratio of 1 to 5. As inflows to the system, a typical dry weather flow pattern from Norwich, and a rainfall time series of one week's duration have been used here.

In the simple example considered here, three control handles are taken into account. These include the maximum capacity ("throttle flow") of the last pipe in the sewer system, the maximum treatment plant inflow capacity and the threshold value triggering emptying the storm tank at the treatment plant: when the inflow rate to the plant (sensor information) drops below this threshold value, the contents of the storm tank is pumped back into the system (using a pre-defined pump rate). Sensor input and control output of the algorithm are denoted by "A" and "S" in Figure 1. Optimisation of the settings of these three parameters was carried out for the two concomitant objectives of maintaining a good balance of dissolved oxygen (DO) concentrations (expressed here by the duration of time periods of critically low DO) in the river and by maintaining a good balance of ammonium concentrations in the river (expressed here by the duration of time periods of ammonium concentrations exceeding a critically high value). These criteria and the related threshold values have been derived from the Urban Pollution Management criteria (FWR, 1994). Other researchers use different, but similar, criteria (Lau et al., 2002).

Figure 5 shows the results obtained after application of the Evolutionary Strategies. Each data point represents a control algorithm, the performance of which is shown with regard to the two biological criteria defined above. "Ideal" control would be characterised by a minimum of the durations of the critical time periods with regard to both criteria. It can be clearly seen in the figure that there is a trade-off between a good oxygen balance and a good ammonium balance in the river.

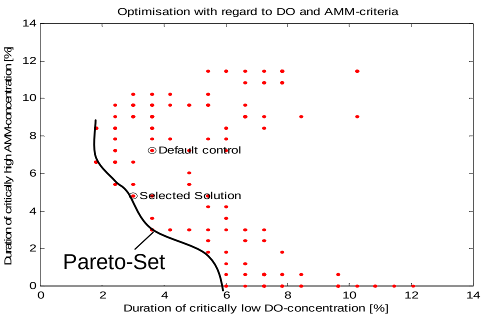

Figure 5: Optimisation using Evolutionary Strategies

Figure 5 also contains the data point marking the performance of the "Default control" case, i.e . the scenario for which literature values are applied. Furthermore it can be seen that optimisation with regard to just one criterion (e.g. DO) does not necessarily result in good performance with regard to other criteria as well. From the set of "non-inferior solutions" (in the lower left of the chart), i.e. those solutions for which improvement with regards to one criterion leads to deterioration with regard to the other criterion, a data point (representing a control algorithm) can be selected, which fits best the specific needs of the control problem. The chart allows to take a balanced decision, considering the trade-off between the objectives.

For example, the data point (3.01, 4.82), marked with "Selected Solution", appears to be a good solution - yielding good system performance with regard to both criteria, oxygen balance and ammonium balance. Using the simulation tool, it is now possible to simulate the selected control algorithm and to analyse its behaviour in detail. Figure 6 shows a comparison of the minimum DO concentration (at any location in the river) between the control algorithm represented by this solution and the default control scenario.

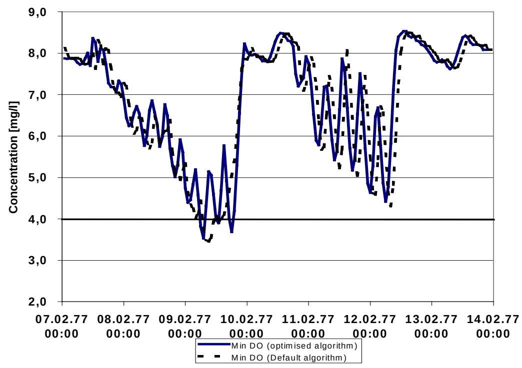

Figure 6: Dissolved Oxygen balance when applying the selected control algorithm

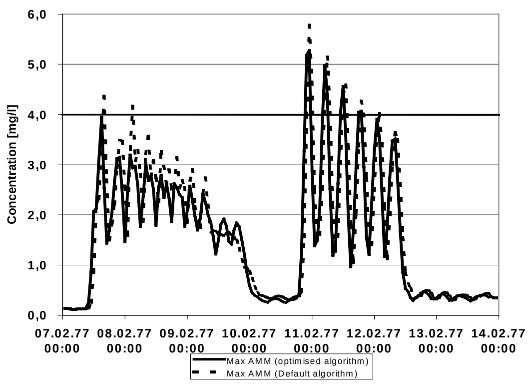

Figure 7: Ammonium balance when applying the selected control algorithm

Similarly, Figure 7 illustrates the maximum ammonium concentration in the river when applying each of both control scenarios. It can be seen that, applying the optimised control algorithm, indeed an improvement of the oxygen and of the ammonium balances in the river can be achieved. This holds true in particular for the first part of the rain event series simulated here.

7 CONCLUSIONS

Using a simple example, this paper has developed and demonstrated a methodology to consider several concomitant objectives in the operation of urban wastewater management, based on a detailed representation of the system (using a simulator) and by application of a multi-criteria evolutionary optimisation algorithm. Obviously for practical application of this methodology to the design of controllers and control rules and to the tuning of their parameters, further work needs to be done, in particular with regard to coping with potentially large numbers of parameters to be optimised. Results obtained so far, however, are encouraging and clearly demonstrate the potential of application of these methods of controller design and optimisation for the management of urban wastewater system, thus contributing to a better urban environment.

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