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Wastewater treatment: New insight provided by interactive multiobjective optimization

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A B S T R A C T

In this paper, we describe a new interactive tool developed for wastewater treatment plant design. The tool is aimed at supporting the designer in designing new wastewater treatment plants as well as optimizing the performance of already available plants. The idea is to utilize interactive multiobjective optimization which enables the designer to consider the design with respect to several conflicting evaluation criteria simultaneously. This is more important than ever because the requirements for wastewater treatment plants are getting tighter and tighter from both environmental and economical reasons. By combining a process simulator to simulate wastewater treatment and an interactive multiobjective optimization software to aid the designer during the design process, we obtain a practically useful tool for decision support. The applicability of our tool is illustrated with a case study related to municipal wastewater treatment where three conflicting evaluation criteria are considered.

1. Introduction

Operational requirements of wastewater treatment plants (WWTPs), notably the effluent limits of nitrogen and phosphorus, are getting tighter and tighter because of increased emphasis on environmental values. Consequently, more complex wastewater treatment processes are gaining ground. At the same time, the needs for economical efficiency (for example, minimizing plant footprint and the consumption of chemicals and energy) as well as for operational reliability are also emphasized. This makes the design of a WWTP a complex process involving trade-offs between a number of conflicting economical and operational criteria. Therefore, a simplified approach where all the aspects are gathered together, usually as estimated total costs, and optimized is not adequate anymore. Instead, there is a need for decision support tools that can take simultaneously into account these different criteria and help the designer in analyzing their interdependencies. This kind of an approach enables getting a much more realistic idea on how the WWTP plant should be designed while balancing between conflicting criteria.

Handling with problems involving multiple conflicting criteria (or objectives) is called multiobjective optimization and many methods have been developed for such problems (see, e.g., [3,4,16,18,29]). Assuming the problem has been correctly specified, the methods usually concentrate on Pareto optimal solutions, also known as compromise solutions, where none of the objective values can be improved without impairing at least one of the others. Solving multiobjective optimization problems can be understood as finding the Pareto optimal solution that best satisfies the needs of a decision maker (DM). This person can be, e.g., a designer when we are talking about practical applications like WWTP design. Thus, the final solution of a multiobjective optimization method is often referred to as the most preferred solution.

The class of interactive multiobjective optimization methods (see, e.g., [18,25] and references therein) is a widely used one consisting of different approaches that iteratively proceed towards the most preferred solution and the DM can learn about the interdependencies among the objectives during the solution process and adjust one's preferences accordingly. An alternative approach is to compute a representative set of Pareto optimal solutions (note that there can be infinitely many Pareto optimal solutions) and let the DM choose the most preferred solution afterwards. A benefit of using interactive methods for decision support is that they generate Pareto optimal solutions based on the DM's preferences and when the DM changes one's preferences, a new or some new Pareto optimal solutions are obtained and the DM does not need to consider uninteresting solutions.

To guarantee a final design which takes into account all the relevant criteria related to wastewater treatment, we propose an interactive design strategy that utilizes numerical simulation of wastewater treatment processes combined with an efficient interactive

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multiobjective optimization method, NIMBUS [24]. Complex characteristics of wastewater treatment processes can be quantified by using numerical simulation techniques. The resulting WWTP design problem is thus simulation-based which means that the values of the objective and constraint functions consist of outputs of a process simulator. The approach combining numerical simulation with interactive multiobjective optimization enables the designer to simultaneously consider the process from different perspectives and optimally balance the final design between different conflicting design criteria.

The WWTP design problem has been previously considered by optimizing only one objective function, that in one way or another describes the costs of the process to be minimized (see, for example, [5,13,15,28]). So far, very little attention has been given to approaches utilizing multiobjective optimization. Actually, we have found only two papers in this field that deal with multiple objectives. In [2], the idea is to produce a representative set of Pareto optimal solutions to the multiobjective optimization problem considering WWTP design. Let us also point out that the approach in [2] is not of simulation-based optimization as is the case in our study but considers the problem in a more general level without using numerical simulation. In [6], multiple objective functions are considered in conceptual design of activated sludge systems. A multiobjective methodology is used to evaluate and compare a small number of alternatives resulting from conceptual design. However, none of these approaches consider interactive methods that enable the designer to actively participate in the design process.

In this paper, we concentrate on utilizing modern optimization techniques to provide a decision support tool for the designer which helps him/her to locate the best trade-offs between different competing design alternatives in WWTP design. By utilizing interactive multiobjective optimization in the design process, the designer is able to learn about the problem and about the interdependences between the conflicting design criteria. As mentioned, (s)he can concentrate only on those solutions that are of interest to him/her. When compared to the approach in [2], our interactive approach is more computationally efficient, that is, the required number of Pareto optimal solutions computed is smaller because we do not try to approximate all the Pareto optimal solutions of which many can be uninteresting to the designer.

Our interactive design tool proposed consists of combining numerical simulation of wastewater treatment processes by the GPS-X process simulator with the interactive multiobjective optimization capabilities of the IND-NIMBUS optimization tool [21]. As already discussed, this kind of an interactive design tool is an entirely novel approach in WWTP design (the first ideas of the tool were presented in [10]), although such tools are successfully utilized in other application fields. The possibilities of this interactive design tool are here illustrated by reporting results from a case study which deals with the optimization of a WWTP operation in terms of energy and chemical consumption, operational safety and effluent quality.

The rest of this paper is organized as follows. First, in Section 2, we briefly introduce wastewater treatment and describe the case study problem we are considering. Section 3 is devoted to introducing the interactive multiobjective optimization method we are using, namely NIMBUS and its implementation IND-NIMBUS. In addition, we describe the structure of the proposed interactive design tool and show how to use its graphical user-interface. In Section 4, we report the results of applying the new design tool to the case study described in Section 2 along with some discussion of the results obtained. Finally, we make some concluding remarks about the study and summarize topics for future research in Section 5.

2. On modelling wastewater treatment

2.1. Background

Mathematical modelling of WWTPs began gaining ground in the 1990s when experience on modelling techniques and computing power increased simultaneously. In the literature, the overwhelming majority of modelling considers the activated sludge process (ASP), globally the most common method of wastewater treatment. In this process, biomass (which is called activated sludge) suspended in the wastewater to be treated is cultivated and maintained in an aerated bioreactor. The wastewater is purified, i.e. organic carbon, nitrogen and phosphorus are removed, during its retention in the bioreactor. The bioreactor is followed by a clarifier basin, in which the biomass is separated by gravitational settling and returned to the bioreactor, and the treated wastewater is directed as overflow to further treatment or to discharge. Excess activated sludge is removed from the process and treated separately. A schematical flow sheet of the process is presented in Fig. 1.

The activated sludge model (ASM) family developed by the Task Group of International Water Association has been established as a standard for ASP modelling [12]. These are mechanistic models, in which the various phenomena occurring in the bioculture are described by first to third order differential equations. The reaction rates of different substances, e.g., fractions of organic carbon and nitrogen, are obtained by integrating the differential equations over time and factoring them with substance-specific stoichiometric coefficients. These coefficients are based on continuity of key parameters (including total chemical oxygen demand, total nitrogen, total phosphorus and charge), which ensures model integrity. The models are nonlinear, reflecting the nonlinear nature of microbial growth and solids separation.

2.2. Optimization in WWTP design

As new treatment requirements prompt the use of more complex processes, the number of independent (and dependent) variables in the design task increases, and selection of their optimal values becomes more difficult without appropriate support. Considering different objectives (treatment results, investment costs and operational costs) and different environmental conditions in which the plant has to operate (wastewater quality, flow and temperature fluctuations) significantly increases the complexity of the problem. The optimal design and operation of a wastewater treatment plant involves, e.g., selecting appropriate volumes and functions for process units and determining optimal setpoints for dissolved oxygen concentrations, sludge circulation flows and chemical dosing rates such that they optimize the behaviour of the plant, according to some pre-defined criteria, in given conditions [1]. Mathematical models are a powerful tool for this kind of optimization problems.

Optimization of WWTP design and operation by modelling and simulation has been applied since the 1990s. The studies usually involve comparisons of different process schemes or control strategies. The behaviour of the considered solutions is simulated, and the results are then compared to each other, usually in terms of investment or operational costs. The comparison can be done either by engineering judgement, as is usually the case (see e.g. [7,17]) or using a single objective optimization algorithm (see e.g. [5,28]). However, formulating the problem so that all relevant criteria are combined as a single criterion and using only this objective function instead of individual objective functions for each criterion hides the interdependencies between different criteria and, thus, makes it difficult for the DM, who might be, e.g., a designer or a plant operator, to assess the true optimality of the solution. The DM may also have non-quantifiable priorities, such as operational stability and ease of operation, which may depend on many decision variables to be optimized. For example, minimizing the concentration of activated sludge to avoid settler overload may be more important than minimizing certain residual pollutant concentrations in the effluent. Therefore, for a truly optimal design, the procedure must present the DM with solutions based on a multiobjective optimization approach, out of which (s)he can choose the best ones to be elaborated further.

Because dealing with a pre-specified single function to be optimized is not appropriate in the presence of conflicting criteria,