Environmental Modelling & Software 84 (2016) 177–192

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

An integrated knowledge-based and optimization tool for the sustainable selection of wastewater treatment process concepts

A. Castillo [a, c, *], P. Cheali [b], V. Gómez [c], J. Comas [a], M. Poch [a], G. Sin [b]

[a] Laboratory of Chemical and Environmental Engineering (LEQUIA), University of Girona, Science Faculty, Montilivi Campus, 17071 Girona, Spain
[b] CAPEC-PROCESS, Department of Chemical and Biochemical Engineering, Technical University of Denmark, Building 229, DK-2800 Kgs. Lyngby, Denmark
[c] AQUALOGY (SUEZ), Passeig de Zona Franca 48, 08038 Barcelona, Spain

ARTICLE INFO

Article history:
Received 15 October 2015
Received in revised form
1 June 2016
Accepted 23 June 2016

Keywords:
IEDSS
Optimization
Integration
WWTP process selection
Uncertainty

ABSTRACT

The increasing demand on wastewater treatment plants (WWTPs) has involved an interest in improving the alternative treatment selection process. In this study, an integrated framework including an intelligent knowledge-based system and superstructure-based optimization has been developed and applied to a real case study. Hence, a multi-criteria analysis together with mathematical models is applied to generate a ranked short-list of feasible treatments for three different scenarios. Finally, the uncertainty analysis performed allows for increasing the quality and robustness of the decisions considering variation in influent concentrations. For the case study application, the expert system identifies 5 potential process technologies and, using this input, the superstructure identifies membrane bioreactors as the optimal and robust solution under influent uncertainties and tighter effluent limits. A mutual benefit and synergy is achieved when both tools are integrated because expert knowledge and expertise are considered together with mathematical models to select the most appropriate treatment alternative.

1. Introduction

In the last few decades, public awareness regarding water scarcity and pollution, together with the current water legislative framework, has involved an increase in the number of wastewater treatment facilities. In this context, the selection of the WWTP configuration or process flow diagram is a considerable challenge; hence, knowledge from experts, including wastewater researchers as well as practitioners (i.e., wastewater engineers and operators), is required.

Quaglia (2013) illustrates the process of selection and design of a WWTP configuration as a funnel approach composed of four steps (Fig. 1). In phase I, knowledge-based systems, including intelligent environmental decision support systems (IEDSS), can be applied to select the most feasible alternatives from the market technologies based on technical, economic, environmental and social criteria. In phase II, optimization tools, based on mathematical methods, allow selecting short-listed candidates among those previously considered. In phase III, the alternatives from the previous phase are evaluated using rigorous and dynamic models to obtain the optimal process parameters. In the last step (phase IV), detailed engineering design is performed for the selected alternative.

The first two steps of Fig. 1 can be addressed considering two approaches; in the first, experts select the “best” alternative, taking into account their expertise and knowledge and therefore relying on intuitive methods (Kalbar et al., 2013), which could lead to subjective and biased decisions. The second method is to apply mathematical-based optimization to solve the problem such that objective decision-making is achieved using more quantitative analysis (Bozkurt et al., 2015). In a mathematical optimization-based approach, however, expert knowledge is needed, particularly to define the design space for the alternatives to be included in the optimization as an off-line expert intervention, but a systematic reasoning procedure is not followed. Therefore, an integrated approach that combines the knowledge from different experts and the quantitative nature of optimization will allow obtaining a more comprehensive analysis and solution of the optimal WWTP process selection problem. However, experts commonly select traditional solutions because it is difficult to develop an integrated analysis without the proper tools (Chamberlain et al., 2014).

* Corresponding author. Laboratory of Chemical and Environmental Engineering (LEQUIA), University of Girona, Science Faculty, Montilivi Campus, 17071 Girona, Spain.
E-mail addresses: acastillo@aqualogy.net (A. Castillo), pche@kt.dtu.dk (P. Cheali), vgomez@aqualogy.net (V. Gómez), joaquim.comas@udg.edu (J. Comas), manel@lequia.udg.edu (M. Poch), gsi@kt.dtu.dk (G. Sin).

http://dx.doi.org/10.1016/j.envsoft.2016.06.019

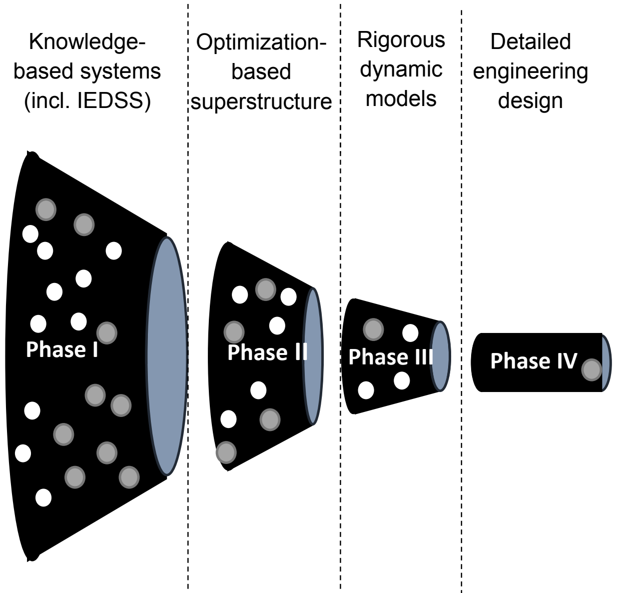

Fig. 1. Funnel approach where different steps in the selection and design of an alternative WWTP configuration process (Quaglia, 2013), together with the tools applied in each step, are represented.

Different methodologies have been developed to improve treatment selection, but most of them do not consider the entire wastewater treatment process (Gómez-López et al., 2009; Huang et al., 2015), or they lack an integrated assessment because they do not consider the set of economic, environmental and technical criteria (Kilic and Hamarat, 2010). Other studies include a very limited number of wastewater treatment alternatives, which restricts the range of technologies considered (Zeng et al., 2007; Makropoulos et al., 2008; Huang et al., 2015).

Moreover, most of the studies mentioned previously have been performed focusing on one of the different steps of the decision concerning WWTP concept selection and design (Bozkurt et al., 2015). Thus, none of them address more than one of the steps involved in Fig. 1. Therefore, there is a research need to integrate different types of expertise with mathematical models and optimization to improve the quality of the results. In addition, research is also needed to properly handle the multi-objective and uncertain characteristics involved in the decision-making of selecting an optimal alternative for wastewater treatment plant configuration (Zeng et al., 2007; Garrido-Baserba et al., 2012).

As regards phase I, knowledge-based techniques have been used for the conceptual WWTP design under a multi-criteria analysis by the application of an IEDSS. NOVEDAR_EDSS (Garrido-Baserba, 2013) consists of a knowledge-based system that applies a hierarchical approach, a structural network model, decision trees, a recursive evaluation and a multi-criteria analysis to complete this step. This tool efficiently explores different alternatives based on several technical, economic and environmental criteria by means of parameters (e.g., removal efficiency, costs and emissions) and indicators (e.g., life cycle analysis (LCA) and shadow prices), which should contribute to the development of more efficient and environmentally friendly urban wastewater treatment plants.

Concerning phase II, the superstructure-based optimization methodology is applied to identify the optimal WWTP network configuration from the list generated in the previous step (Bozkurt et al., 2015). This is a novel framework to help with effective formulation and management of the complexity of an early-stage design of a WWTP. This tool applies a superstructure-based optimization method to generate the design space as a process network, i.e., a so-called superstructure. Because this method focuses on designing processes at the early stage (where the availability and accuracy of data are limited), it can also be used to short-list a number of the most promising processing alternative (e.g., the first three solutions as shown in Bozkurt et al., 2015), which can be used in the next phase for detailed analysis.

As phases III and IV (outside the scope of this work) comprise the final steps in the WWTP design process, they address the application of rigorous dynamic models and detailed engineering design, correspondingly.

NOVEDAR_EDSS and the optimization tool are two tools that have been demonstrated to properly perform the selection of the best treatment alternative in steps I and II of Fig. 1, correspondingly. The aim of this study is therefore to develop a comprehensive framework that effectively addresses the steps of conceptual design (phase I) and optimization (phase II) in the technology selection process by integrating knowledge-based systems with mathematical models. The new framework introduces the following novelties: 1) multi-criteria sustainability screening of the promising treatment concepts using IEDSS; 2) superstructure formulation based on the promising treatment concepts obtained in (1) and detailed dimensioning, optimization and analysis; and 3) sensitivity analysis to test the robustness of the selected concepts.

The proposed comprehensive framework will utilize the advantages of both NOVEDAR_EDSS and the optimization tool, and it will then be applied to an actual wastewater treatment problem as a case study for verification and demonstration purposes. The paper is structured as follows: first, the integration methodology, together with the IEDSS and the optimization tool, is presented. Then, the selected case study to be solved by applying the integrated approach is explained. Finally, the results obtained are discussed to identify the benefits of the integration.

2. Integrated methodology

Because the aim of this study is to consider the potential benefits of integrating NOVEDAR_EDSS and the superstructure-based optimization, in this section, the integrated methodology applied for selection of the WWTP configuration, comprising phase I and phase II, is described. This methodology includes the workflow for the integrated framework consisting of three different steps (Step 1 to Step 3, Fig. 2), which are interconnected to perform the alternative selection considering static models. **Step 1,** which corresponds to phase I (Fig. 1), addresses the NOVEDAR_EDSS application to explore a wide range of feasible technologies based on the characteristics of the case study selected and considering a knowledge-based multi-criteria approach. Among the treatments recommended by the IEDSS, a short-list is selected to perform the next Step. **Step 2** (corresponding to phase II in Fig. 1) involves applying the optimization tool, which should first be upgraded to obtain the proper superstructure for the specific case study. Then, based on mathematical programming, the optimization tool identifies the optimal network. Finally, **Step 3** (which is part of phase II in Fig. 1) consists of a sensitivity analysis, which is developed by the optimization tool to ensure the robustness of the decisions.

Step 1: Intelligent/expert screening of process technologies in NOVEDAR_EDSS.

NOVEDAR_EDSS integrates different knowledge-based techniques to perform the pre-selection of the process flow diagram in a WWTP. This tool was developed following the five steps proposed by Poch et al., 2004: analysis of the problem, data and knowledge acquisition, cognitive analysis, model selection and integration. The software was verified and validated by different experts from academia and from companies participating in the Consolider and