Environmental Modelling & Software 66 (2015) 153–166

Contents lists available at ScienceDirect

Environmental Modelling & Software

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

Regulatory control analysis and design for sewer systems

Ane Loft Mollerup [a], [b], Peter Steen Mikkelsen [c], Dines Thornberg [d], Gürkan Sin [b], *

[a] HOFOR, Ørestads Boulevard 35, 2300 Kbh. S, Denmark
[b] Technical University of Denmark, Department of Chemical and Biochemical Engineering, Søltoft Plads, B229, DK-2800 Kgs. Lyngby, Denmark
[c] Technical University of Denmark, Department of Environmental Engineering, Miljøvej, B113, DK-2800 Kgs. Lyngby, Denmark
[d] BIOFOS, Refshalevej 250, DK-1432 Kbh. K, Denmark

ARTICLE INFO

Article history:
Received 7 May 2014
Received in revised form
30 November 2014
Accepted 1 December 2014
Available online 24 January 2015

Keywords:
Sewer system control
Regulatory control
Controllability analysis
Pairing

ABSTRACT

A systematic methodology for regulatory control analysis and design is adapted for sewer system operation and evaluated. The main challenge with adapting the methodology is the handling of the stochastic and transient nature of the rainfall disturbances, inherent to sewer system operation. To this end, four distinct modes of operation are identified (dry weather, filling, saturation and emptying) and for each of these the process gain matrix is found. Based on the gain matrices a controllability analysis is performed, to screen for suitable pairings between measurements and actuators in the case study area of Copenhagen. The analysis effectively reduces the number of potential controlled variables, by considering the sensitivity of the measurements towards changes in the manipulated variables. Several potential pairings are generated and the best alternative is chosen for closed-loop testing. The methodology is a promising tool for systematic generation of solutions for sewer system control.

1. Introduction

Controlling a sewer system, such that the operation of the system is adjusted to handle the experienced disturbances, most of them being rainfall occurrences, is a way to optimize the performance of the existing structures. This can among other things lead to a decrease in the volume and frequency of CSOs and thus a reduction in the negative impact on the receiving water bodies, which is in the interest of the water utilities responsible for handling the sewerage water and ensuring the permissions for CSOs are not exceeded. The simplest type of control for any system is often a distributed control structure with single input, single output feedback loops, also known as regulatory control (Larsson and Skogestad, 2000). In Fig. 1 a sewer system process controlled by a feedback loop is illustrated. When a system is controlled by means of a feedback control loop, a measurement of the controlled variable, such as a flow or a level, is made or inferred. The estimated value of the controlled variable is then compared to the desired setpoints and by changing the setting of the actuator (i.e. adjusting the manipulated variable, such as pumps and valves), the controller aims to keep the controlled variable close to its setpoint value. The difference between the setpoint and the measured value of the controlled variable is the error, which should be close to zero. Such a control is also called closed-loop control. If the process (or system) is controlled without feedback it is called open-loop control (Seborg et al. 2011).

The control system for a sewer system can have a hierarchical architecture, with the control layers at the lower levels and the optimising layers at the higher levels (Mollerup et al., submitted for publication). Although a control system with only one layer, the regulatory control layer, has a simple control structure, designing the regulatory control for a sewer system with a large number of sensors and actuators (pumps, valves, gates, etc.) is not a simple task. Examples of important questions that need to be answered include the following: 1) Which measurements to use? 2) How to pair the measurements with the available actuators?

The traditional approach used for designing a control system for sewer system operation is usually experience-based and a highly iterative process, where a large number of possible control system designs are outlined and simulation results compared to find the best solution (Beeneken et al., 2013). To the best of our knowledge

---

Abbreviations: CDS, Chicago design storm; CSO, combined sewer overflow; CN, condition number; CV, controlled variable; f.d.RGA, frequency-dependent RGA; MV, manipulated variable; MAE, mean absolute error; RGA, relative gain array; RMSE, root mean square error; SVD, singular value decomposition; SSE, sum of squared errors; SE, sum of the error.

* Corresponding author. Tel.: +45 4525 2806.
E-mail addresses: molle@hofor.dk, molle@kt.dtu.dk (A.L. Mollerup), psmi@env.dtu.dk (P.S. Mikkelsen), dt@biofos.dk (D. Thornberg), gsi@kt.dtu.dk (G. Sin).

http://dx.doi.org/10.1016/j.envsoft.2014.12.001

no methodological ways of designing the regulatory control for sewer systems are published.

In the field of control engineering a methodological approach however exists that is often used in fields such as chemical engineering (Larsson and Skogestad, 2000), wastewater treatment engineering (Olsson and Newell, 1999; Vangsgaard et al., 2014), etc. This approach, also called a process oriented approach for control system design, employs a set of tools and methods from control and systems theory. It follows a step-by-step procedure to describe the control objective and to perform degrees of freedom analysis, screening of measurements, assessment of measurement sensitivities to changes in the inputs and pairing between measurements and inputs. Using this information the control loops are formulated and closed-loop evaluation of promising control loops are made. Finally, iterations are made if necessary.

However, adapting the methods used in the process oriented approach for control system design (tailored for the needs of process dynamics and operations in chemical and wastewater treatment engineering) to sewer systems is not straightforward and requires a systems analysis approach. The main challenge in sewer system operation is the fact that the disturbances, mainly the rainfall runoffs, are highly stochastic and transient in nature which creates transient dynamics in the sewer system. Nevertheless, the tools from modern control engineering (Seborg et al., 2011) are in principle generic and may still provide insights into the analysis of sewer systems operation and control; provided that the methodology and the methods and tools are adapted to the specific needs of sewer system control.

In this paper a methodological approach for controllability analysis and design of regulatory control is adapted and applied to an example of a sewer system. The application of the methodology is highlighted through a case study – a subcatchment of Copenhagen's sewer system. To be able to maintain the main focus of the study on control aspects, a simulation model (MOUSE) of the catchment areas is used to represent and describe sewer systems input and output dynamics to highlight the application of the methodology.

The paper is organized as follows: first the methodology is described in Section 2 including all the associated methods and tools; then the software used is presented in Section 3 and a case study application of the methodology is presented in Section 4. In Section 5 the results are discussed before providing concluding remarks in Section 6.

2. A systematic methodology for regulatory control design – methods and tools

To solve a control problem two important questions needs answering, among others (Larsson and Skogestad, 2000): 1) What variables are to be controlled, manipulated and measured? 2) How should the controlled and manipulated variables be paired? To analyse and answer these questions in a structured way, a stepwise methodology is proposed that can be seen to the right in Fig. 2.

The methodology presented here aims at regulatory control layer design. This task is in fact part of a larger control design problem of sewer systems, as shown in the left part of Fig. 2 (from Mollerup et al., submitted for publication). Each of the steps of the methodology are described in the following sections 2.1–2.5.

2.1. Step 1: obtain evaluation model

The evaluation model is a dynamic model of the system that can describe the real world with sufficient accuracy. In this context sufficient accuracy is related to the models ability to simulate overflow patterns correctly. The model is used for evaluating the control system. To this end, detailed physically distributed first principles models such as MOUSE/MIKE URBAN (DHI group, 2014), as well as lumped-conceptual models can be used (see e.g. Bach et al., 2014, for an overview), which relate impacts of input disturbances to system output and performance.

The detailed first principle model used by the utility company is readily available. However, the software has an inflexible control toolbox and does not easily exchange data with other systems. Therefore this model is not chosen as the evaluation model. Instead a simple Virtual Tank model representation is selected. The Virtual Tank model is mainly based on maintaining mass balances in the system. The model is chosen because of its simplicity, which makes it relatively easy to implement using any programming language, and its linear properties, which makes it suited for testing control ideas (Ocampo-Martinez, 2010).

2.1.1. Equations of the virtual tank model

The overall virtual tank model includes both virtual tanks that describe subcatchments in an area assuming precipitation and flow to be homogeneous, and real detention tanks (detention basins). The outflow from a virtual tank (subcatchment) is based on the linear reservoir assumption:

$$q_{\text{out}} = \beta_i V_i, \tag{1}$$

where V_i is the volume of water in the tank and the parameter β_i (s^{-1}) is a volume/flow conversion coefficient. β_i can be determined from regression of historical data of flow and level. If the regression is not satisfactory for all ranges of level/flow, β_i can be determined piecewise for two or more ranges at the expense of introducing nonlinearity in Eq. (1).

The mass balance for a virtual tank is expressed as:

$$\frac{\mathrm{d}V_i}{\mathrm{d}t} = q_{\text{in}} + I_{\text{eff}} - q_{\text{out}}, \tag{2}$$

where t is time, q_{in} is the inflow coming from other tanks, virtual tanks and the dry weather flow (household wastewater), I_{eff} is the effective rainfall runoff and q_{out} is the outflow from the virtual tank, empirically modelled as in Eq. (3).

The effective rainfall is the amount of rainfall that actually goes into the sewers. The effective rainfall runoff can therefore be expressed as:

$$I_{\text{eff},k} = A \times a \times I, \tag{3}$$

where A is the catchment area, a is the runoff coefficient (degree of connection times imperviousness) and I is the rainfall intensity.

The mass balance for a real tank is expressed as:

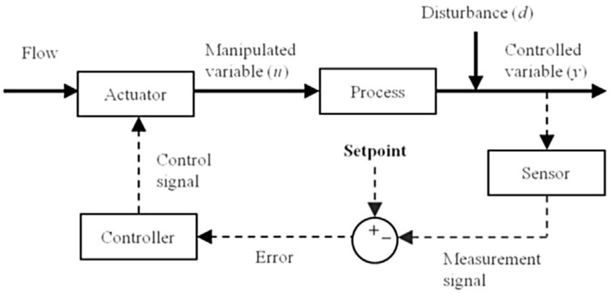

Fig. 1. Feedback control loop for a sewer system. The bold lines are the physical system, while the dotted lines are signals (from Mollerup et al., submitted for publication).