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Model-based analysis of control performance in sewer systems

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Abstract: Design and assessment of control in wastewater systems has to be tackled at all levels, including supervisory and regulatory level. We present here an integrated approach to assessment of control in sewer systems based on modelling and the use of process control tools to assess the controllability of the process. A case study of a subcatchment area in Copenhagen (Denmark) is used to illustrate the combined approach in modelling of the system and control assessment.

Keywords: Sewer system, control, plantwide control, system understanding, modelling

1. INTRODUCTION

Since the EU Water Framework directive came into force in 2000, wastewater systems (sewer system and wastewater treatment plants) in Europe have been put under pressure to reduce the number of combined sewer overflows[1] (CSOs) from the system to protect the aquatic environment. And as the future climate changes are predicted to induce an increase in precipitation in the northern part of Europe (Watson et al., 1997), the strain on the performance of the wastewater systems will only become larger in the future.

To cope with the increasing pressure the wastewater system can be expanded by building larger pipes and new storage tanks. But expanding the wastewater system requires a significant capital investment and intensive civil building works and therefore the need for this should be limited as much as possible. Instead of expanding the system, research has shown that the implementation of Real Time Control (RTC) in the sewer system can increase the utilization of the existing storage volume and thereby reduce the need to build new storage capacity (Marinaki, Papageorgiou 1997). The use of RTC allows for the control of pumping stations and diversion or retention gates according to online measurements at critical points, thereby making it possible for the system operation to respond to rain events.

To further increase the utilization of the system, research is now primarily focused on how to do a system wide optimization. In particular, research on how to use real time optimisation (RTO) and model predictive control (MPC) in the control structure.

The problem of finding the optimum control structure that best serves both the sewer system and wastewater treatment plant(s) is a challenging and formidable problem. The main objective of the control system is to minimize the risk of flooding and the volume of overflow and bypass from the system.
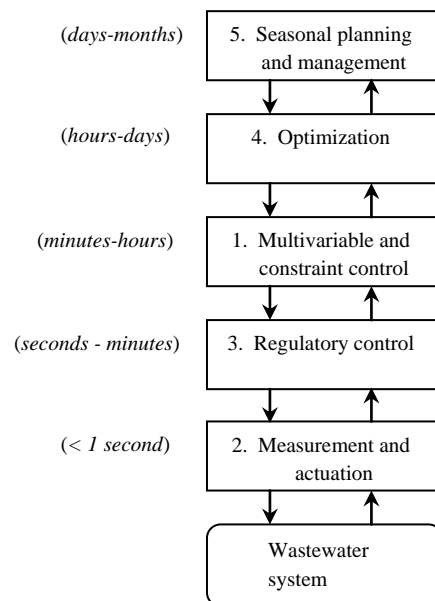
Fig. 1: The system decomposition with respect to time scale (based on Seborg et al. (2011)).

One way to address the control problem is to decomposition it according to the time scales of the actions. From this it becomes possible to identify a number of layers, linked by

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[1] Combined Sewer Overflow: The discharge from a combined sewer system that handles both wastewater and stormwater. During rain the system can discharge from overflow structures into a recipient such as a stream, river, lake or sea, if the capacity of the system is exceeded.

master-slave relations. For the sewer system the decomposition can look as depicted in figure 1.

Based on decomposition one can look at the different levels of control separately, starting from the lowest level and moving upward.

Using the system decomposition it becomes obvious that the research today on control of the wastewater system is focused on higher layers in the system decomposition. However these methods are supervisory layer controllers that require a control structure as given. Therefore it becomes imperative that the regulatory level control functions optimally.

However, in practice the design and implementation of RTCs in wastewater systems have been done incrementally as the utility management companies have identified the potentials. Over time as more and more controls have been implemented in the wastewater system and the number of controlled actuators in the system has increased, important interactions among the different control loops may have appeared, that was not accounted for in the design of the individual controls. Depending on the interactions among the control loops this may appear impairing on the performance of the control system. Therefore attention should be paid to aspects related to the regulatory level such as the analysis of controllability properties of the system according to the design of control loops, pairing of variables, among others. This analysis of control problem and designing of control structure needs to be performed in a formal and structured way as required by process control engineering good practice (e.g. see (Skogestad 2002).

The aim of this work is therefore to formulate the problem of design and analysis of the regulatory level from a process control perspective and to develop a methodological approach to find the optimal solution.

2. METHODOLOGY

The methodology is developed assuming a hierarchical vertical problem decomposition based on time scale as it has been done with similar methodologies aimed at chemical processes. Other approaches in control design for whole plants are i) horizontal decomposition based on process units, ii) vertical decomposition based on process structure; and iii) vertical decomposition based on control objectives (Larsson, Skogestad 2000). These approaches are considered unsuitable for the following reasons. The horizontal decomposition approaches are unable to tackle material recycle (e.g. pumping water back to a previous tank) and assumes large buffer tanks between units (Douglas 1988). The process structure decomposition consists on splitting the process at different levels of representation (e.g. batch vs continuous, input-output) but it has been formulated for chemical plants and it is difficult to adapt to other processes. Finally, the control objective approach establishes different tasks for control (inventory, product specification, equipment constraints, economic performance) but fails to consider the cases where such tasks can lead to contradictory objectives (Price, Lyman & Georgakis 1994).

2.1 Generic approach to the control assessment problem

A suitable solution to the problem of control assessment should not only point out the deficiencies in the system but also address potential solutions to solve them. However, as stated previously, the approach cannot be that of pure design given that the capital cost of modifications in the control system of sewer system is very high and involves works in the public domain. The assessment should lead to incremental modifications that, albeit suboptimal, are feasible.

We propose here to carry out a decomposition of the system with respect to time in different layers linked by master-slave relations (Fig. 1). Such decomposition has been applied in chemical processes as a way to manage the complexity of control design. The methodology consists on the review of each of the control layers, their assessment and proposal of solutions and an eventual evaluation step.

To this respect, the classic indexes will be tested (relative gain array, closed-loop disturbance gain) as indicators of process controllability and ability to reject disturbances. The adaptation of controllability indexes to describe sewer systems will be investigated and new indexes will be proposed if appropriate.

3. CASE STUDY

The approach proposed for the control system assessment is illustrated here through an actual case study described below. The analysis was done considering three scenarios, namely:

1. Dry weather

2. Low intensity rain

3. Moderate intensity rain

Since the primary objective of the control system is to minimise the overflows to the environment, the scenario 3 (moderate intensity rain) is arguably the most relevant. No overflow is expected during dry weather or low intensity rain. Nevertheless, the energy consumption of the pumps is mainly related to the operation during scenarios 1 and 2 since they represent the normal operation. Therefore, they should also be investigated in order to achieve an energy efficient operation as well.

The evaluation of the system is performed with simulation of a long time period (in this work 30 years), using as an input historical rainfall data. The key performance indicators (KPI) are the number of CSO, the volume of the overflows, their frequency and the flooding episodes (overflows from virtual tanks).

3.1 Description of case study area.

The subcatchment area analysed in this work is a part of Copenhagen (Denmark) sewer system (Fig. 2), owned and maintained by Copenhagen Energy. It has a size of Y hectare, X km pipes and is additionally composed of 3 pumping stations, 2 storage tanks and 1 pipe basin. The inflows to the system are the wastewater dry weather flow and rainfall and the outflows are five flows to the environment (caused by

overflow) and a pipe that directs the flow downstream for treatment.
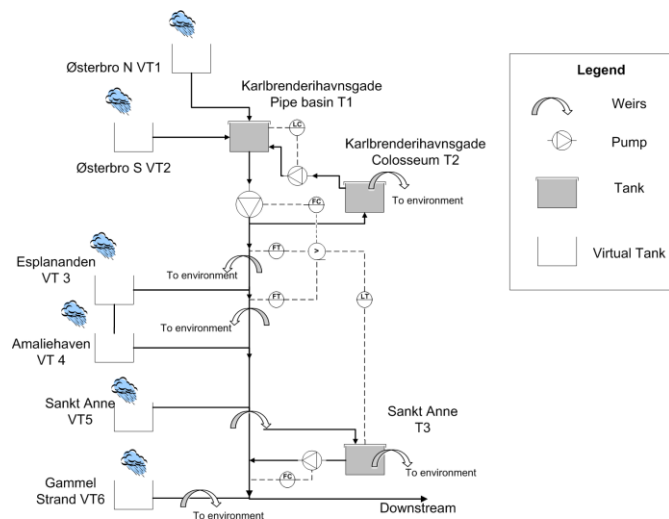

Fig. 2. Map of case study area.

Fig. 3. Modelling the case study using virtual tank approach

The implemented control system of the area is composed of three decentralized loops as follows:

-Loop 1.Controls the level in the tank (T1) manipulating the outflow from the tank (T2), with a larger storage capacity.

-Loop 2. Selective control which manipulates the outflow from tank (T1) to the variable which is further from the setpoint among i) the flow measured downstream the pumping station, ii) the flow in the pipeline after the virtual tank (VT 3) and iii) the level of tank (T3)

-Loop 3. Manipulates the outflow of tank (T3) according to the flow downstream the pumping station.

3.2 Sewer system modelling

The catchment area and sewer system were modelled through the virtual tank approach (Ocampo-Martinez 2010). Virtual tanks are regions of the subcatchment area where the precipitation and flow are considered to be homogeneous. The global mass balance for a virtual tank is expressed as:

$$\frac{dV_i}{dt} = q_{in} + P_{eff} - q_{out} \tag{1}$$

where q_{in} is the inflow coming from other tanks, virtual tanks and the dry weather flow (household wastewater), I_{eff} is the effective precipitation and q_{out} is the outflow from the virtual tank, empirically modelled as:

$$q_{out} = \beta_i V_i \tag{2}$$

The parameter β_i (in s^{-1}) is a the volume/flow conversion coefficient (Ocampo-Martinez 2010). It can be determined from regression of historical data of flow and level. If the regression was not satisfactory for all the ranges of level/flow, β_i can be determined piecewise for two or more ranges at the expense of introducing a nonlinearity in (2). Indicators of wastewater composition have also been included and are modelled considered the virtual tanks as completely mixed:

$$\frac{dV_i C_j^i}{dt} = q_{in} C_j^{in} - q_{out} C_j^i \tag{3}$$

where the index i represents the virtual tank and j the compound considered. The compounds considered are the chemical oxygen demand (COD), total nitrogen compounds (TN), total phosphorous compounds (TP), and total suspended solids (TSS). It is assumed that precipitation has negligible concentration of these compounds and, consequently, does not appear in (3).

The tanks in the system have been modelled as completely mixed compartments and their outflow is assumed to be perfectly controlled by the corresponding control loops (level versus pumps).

Weirs are elements that are used to moderate the flow downstream (e.g. before a pipe node) and to prevent the backwater effects. Since weirs do not have storage capacity, they are modelled as:

$$q_{out} = \begin{cases} q_{in} & if \ q_{in} \leq q_{max} \\ q_{max} & otherwise \end{cases} \tag{4}$$

Finally, pumps are modelled as perfect actuators, immediately setting the flow to the desired value.

3.2.1 Overflow modelling

The modelling of overflow is a key step, given that the objective of sewers system control is precisely to minimise the overflow to the environment (river, lakes, sea…). However, it should be noted that not all the overflows streams are spilled onto the environment; a number of them

are directed to other tanks or virtual tanks according to the links in Fig. 3. Overflow has been modelled as follows:

-From virtual tanks and tanks. The subcatchment areas are divided into smaller zones for which a maximum level (and therefore a maximum volume) is assumed before flooding. For tanks, a maximum storage capacity is known. Overflow is formally calculated the same way for the two structures as:

$$q_{overflow} = \begin{cases} 0 & if\ V \leq V_{max} \\ q_{in} - q_{out} & otherwise \end{cases} \qquad (5)$$

-From weirs.

$$q_{overflow} = \begin{cases} 0 & if\ q_{in} \leq q_{max} \\ q_{in} - q_{max} & otherwise \end{cases} \qquad (6$$

3.2.2 Dry weather flow modelling

Dry weather flow is the flow in the sewers system not influenced by a rain event. For an urban sewer system, it corresponds to the wastewater produced by households in the area covered by a virtual tank. Its contribution to the total flow during any rain event is in general negligible. However, it is important to take it into account since it is the source of polluting agents that can be spilled in case of overflow.

Dry weather flow has been modelled through as a four term harmonic function of periods 24h/12h (Breinholt et al. In Press) or by regression to a 3rd degree polynomial, repeated as an input with period 24h (Sin et al. 2008). In this work, the dry weather flow was simulated by a 24 piecewise function (each piece consisting of a straight line interpolating a 1h period) built from actual operation data (Fig. 4)

The COD, TN, TP and TS concentration of the dry weather flow was determined taking into account the amount of equivalent-persons per area covered by each virtual tank (Tchobanoglous, Burton 1991).
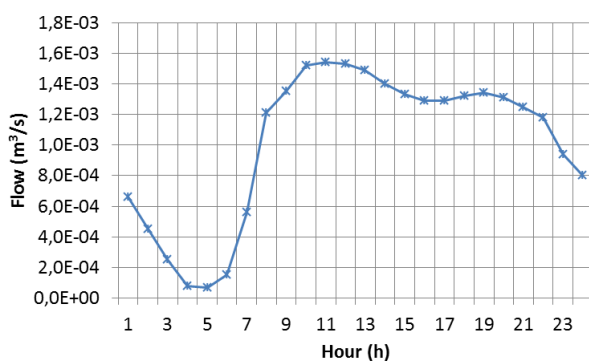

Fig. 4. Dry weather flow hourly variation

3.2.3 Precipitation modelling

To carry out the three-scenario analysis, box rain was used in order to reach a suitable steady state. As for the evaluation of the control base case and proposed improvements, historical rain data were used corresponding to the last 30 years in the subcatchment area. Other approaches in evaluation reported

in literature are based on the use of designed rain events with a certain return period, in particular the so-called Chicago designed storm (Huff, Vogel & Changnon Jr 1981). However, it has been reported that, since designed rain events can overestimate or underestimate the actual rainfall of different region, sewer systems evaluations should be done with historical data or with rain events designed in purpose for a region (Raso, Malgrat & Castillo 1995).

4. CONCLUSIONS

An assessment of sewer system control was carried out by a model-based approach. It was illustrated with a case-study corresponding to a subcatchment area in Copenhagen (Denmark). Future work on this project will consist on the evaluation of the control system with historical precipitation data.

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