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Fuzzy Decision Making for Multi-criteria Optimization in Integrated Wastewater System Management

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Abtract
Integrated modelling is an evolving tool that allows revealing additional potential for control and performance of urban wastewater systems. Still, most research is limited to single-criteria optimization. Multi-criteria optimization is mostly tackled by methods of Pareto optimization accompanied by high computational effort. This computational load problem is amplified when applied to integrated models of urban wastewater systems. Alternatively, fuzzy decision making has been tested for multi-criteria optimization in various applications showing advantages in transparency and computational effort. Therefore the presented study focusses on investigating fuzzy decision making for multi-criteria optimization of sewer networks and sewage treatment works regarding the balance of ecologic and economic criteria. Based on a case study in Luxembourg, a simplified hydrologic model for minimizing combined sewer overflows by real-time control is the cornerstone of the emission-based integrated modelling of the urban wastewater system that also includes a sub-model of the wastewater treatment plant Heiderscheidergrund. Expected outcomes will be a new mathematical tool to optimise the integrated operation of urban wastewater systems. Given the sensitive character of the Haute-Sûre storage lake the anticipated reduction of pollution load to the receiving water will contribute to the final goals of the European Water Framework Directive.

Keywords: Best management practice, control, cost–benefit analysis, integrated modelling, sewer systems, wastewater treatment

INTRODUCTION

In urban wastewater systems combined sewer overflows (CSO) and wastewater treatment plant (WWTP) effluents are the main emission sources. Studies on integrated management of sewer systems and WWTP have shown advantages over the isolated operation of both subsystems (Muschalla et al, 2009). In particular, a control system based on pollutant loads (Vanrolleghem et al, 2005) and taking into account the current performance of the WWTP provides an additional reduction of pollutant emission into natural water courses (Seggelke et al., 2005). The development of such control strategies is based on integrated modelling including all sub-systems to be considered. Due to the high computational effort of optimization, current modelling of integrated urban wastewater systems focuses on single-objective optimization (e.g. flow streams or pollutant loads) (Muschalla, 2008).

Developments in modelling software and computational resources enabled to tackle the first multi-criteria optimizations of integrated wastewater systems. Muschalla (2008) investigated multi-objective optimization/rehabilitation for an urban drainage system based on multi-objective evolution strategies combining the non-dominated sorting genetic algorithm and self-adaptive evolution strategies. The study is based on an interconnection of a hydrologic sewer model, a simplified WWTP model and a water quality model for the receiving water body. The integrated simulation and optimization tool requires extensive computing time to calculate the Pareto optimal solutions for decision support. Within this solution set a solution is Pareto optimal if one objective cannot be improved without worsening another one. Due to the extensive computing time an integrated Pareto optimization based on a hydrodynamic model of the sewer system linked to a dynamic simulation of the treatment plant seems to be practically infeasible at this time. Fu et al. (2008) propose the multi-objective genetic algorithm NSGA II to derive the Pareto-optimal solutions in multi-objective optimised integrated urban wastewater modelling. Considering an immission based approach, water quality indicators of the receiving water are used as control objectives for integrated real time control (RTC) strategies to minimize CSO volume or frequency and maintaining WWTP effluent standards. Although efforts are undertaken to simplify the integrated model, the high computational demand for deriving the Pareto-optimal solutions only allows for offline development of integrated control strategies. Since the problem with multi-criteria optimization is to find the most appropriate solution within the set of Pareto-optimal solutions, they propose multi-criteria decision making techniques for rational and transparent choice of one Pareto-optimal solution over the others to be selected as control strategy.

OBJECTIVE

Regarding a good ecological status as general objective for the receiving water body (CEC, 2000) the validation of quality criteria in integrated urban wastewater systems becomes more and more multidisciplinary. Moving from emission to immission based approaches both ecological impacts and economical aspects have to be minimised. Therefore, for instance, volume and pollutant loads discharged into receiving waters at CSOs can be interpreted over a wide range. On the one hand the minimised volume discharged to the receiving water Q_2 (see Figure 1) minimises ecological impacts but on the other hand it increases treatment costs at the WWTP. The range of possible interpretations of filling degrees measured through water levels h is therefore significantly related to the weighting of the different optimization objectives which can be linked to ecological and economic terms as well as to process stability (see Figure 1). Additionally the data obtained by measurements from the real system are generally limited by the intrinsic insufficiency of the measuring methods. Beyond this further uncertainties result from the intrinsic deviation between model and reality (Muschalla et al, 2009).

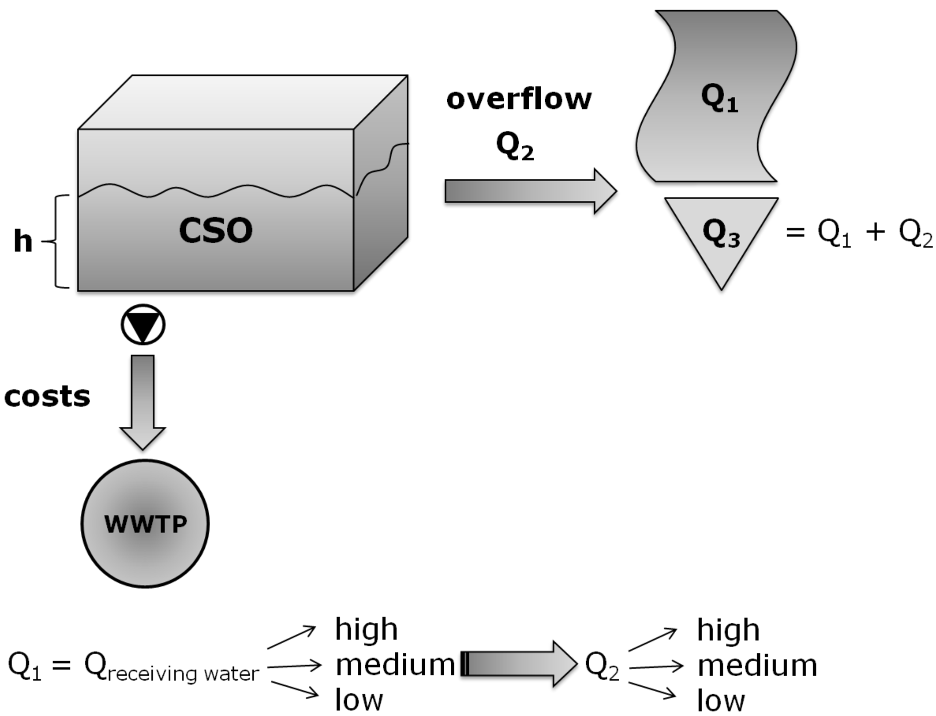

Figure 1. Multidisciplinary quality criteria interpretation

Alternatively to classical Pareto optimization approaches fuzzy decision making (FDM) can be used for multi-criteria optimization (Bellmann and Zadeh, 1970). FDM is based on Fuzzy Logic which is a multi-valued logic derived from Fuzzy Set Theory (Zadeh, 1965). In contrast with classical binary logic the value of variables is not only "crisp" true or false but is allocated to so-called degrees of membership ranging between 0 and 1 as shown in figure 2. Thereby this regards a general intrinsic uncertainty that should not to be mistaken with probabilistic logic that is corresponding to probability.

Fuzzy Logic has been applied to many fields ranging from process control to artificial intelligence and is preferably used for modelling non-numeric linguistic variables. Figure 3 shows the use of Fuzzy Logic Control for combined sewer overflow (CSO) tanks. After fuzzyfication of input variables where the measured water level is allocated through membership functions to 3 different categories ranging between low, medium and high the so fuzzyfied water level is related to a certain discharge Q ranging between low, medium and large. For control of the pump or throttle the discharge Q has to be defuzzyfied by e.g. the center of gravity.

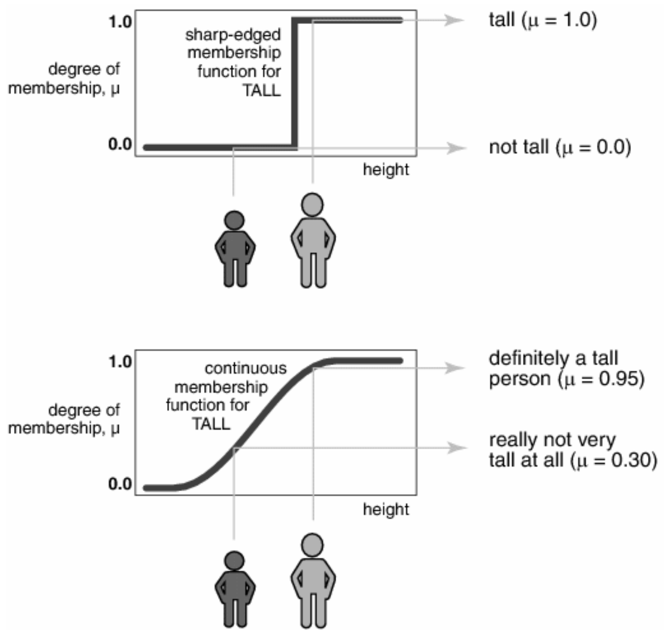

Figure 2. Principle of Fuzzy Logic (source: The Mathworks)

Beside a more sensitive control of CSO tanks Klepiszewski and Schmitt (2002) thereby observed advantages in the design and change process of programs compared to classic rule based control.

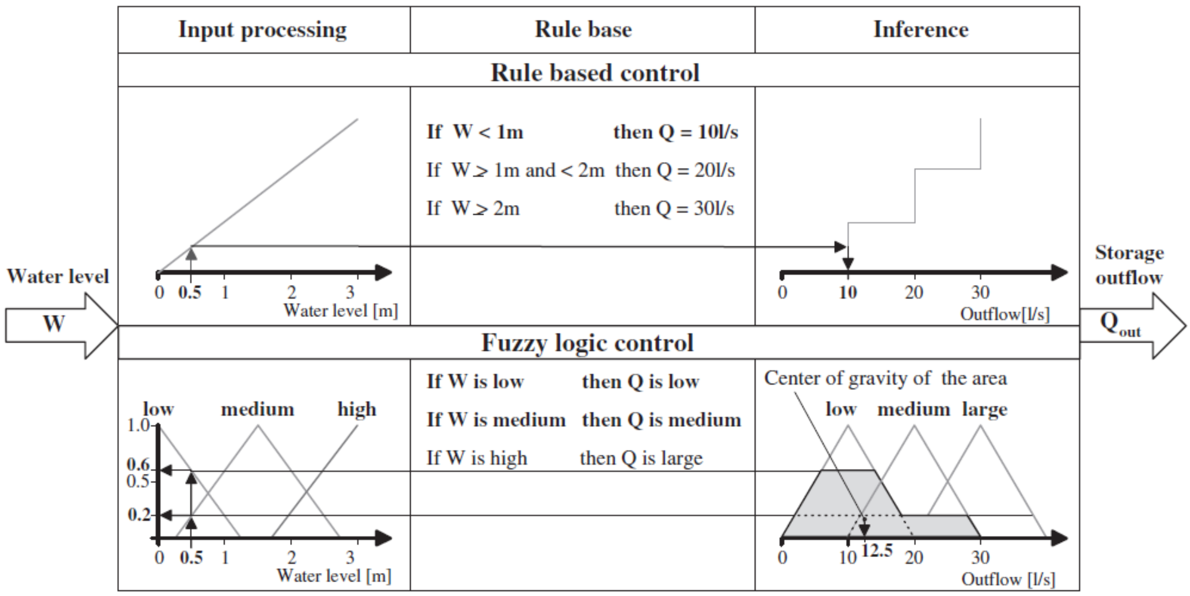

Figure 3. Fuzzy Logic Control (source: Klepiszewski and Schmitt, 2002)

Decision making can be described as the selection of the best alternative from available alternatives out of a Pareto front, given the information regarding the decision problem and the goals of the decision maker (Sousa and Kaymak, 2002). Since decision making resembles the selection of the best available alternative, it can be described mathematically as an optimization problem. In FDM the complexity of multi-objective optimization is minimised by transferring it to a single-objective optimization problem by merging all partial objectives in one substitute quality criteria (Bernard et al, 2001). Thereby the solution is Pareto optimal. Additionally FDM is used for multi-criteria decision aiding in particular in case of fuzzy quality criteria and restrictions as described above. The application of FDM for multi-criteria optimization (MCO) of non-linear and dynamic control systems has been shown in several studies (Bernard et al, 2001) providing advantages in:

- transparent criteria weighting,
- optimal trade-off between performance criteria,
- consideration of different model types (analytical models, fuzzy systems, neural networks, evolutionary algorithms, etc.),
- computational effort.

This paper presents the methodology of FDM for MCO of integrated wastewater systems. It focuses on the development of the integrated sub-models of the sewer system and the WWTP.

METHODOLOGY

Fuzzy Decision Making

In the case of MCO for integrated urban wastewater systems FDM consists of three main steps:

1. Definition of quality criteria:
   According to the requirements of the optimization problem quality criteria of the model have to be chosen. In case of integrated urban wastewater modelling this can, for instance, be the discharged hydraulic load, ammonia, nitrate, energy or total operation costs represented by functions or integrals J_i. These quality criteria are related to controlled variables y_i.
2. Transformation into fuzzy membership functions:
   The quality criteria $J_i(y_i)$ are translated into fuzzy membership functions $\mu_i(y_i)$. This step is done in close cooperation with the different stakeholders and resembles the inherent expert knowledge. Thereby a membership degree equal to one means optimal fulfilment of the objective, equal to zero means unacceptable fulfilment.
3. Weighted optimization and decision making:
   Quality criteria are described by fuzzy goals $\mu_{G1}, \dots, \mu_{Gn}$ and fuzzy constraints $\mu_{C1}, \dots, \mu_{Cm}$. Since both fuzzy goals and fuzzy constraints are desired to have a maximum degree of membership, conflicting objectives cannot compensate each other. The fuzzy decision μ_D is calculated by connecting the fuzzy goals and constraints with fuzzy-AND-operators (e.g. min-operator) to each other. Equation (1) describes the situation for one fuzzy goal and one fuzzy constraint.

$$\mu_D(x) = \mu_G(x) \wedge \mu_C(x), \qquad \wedge = \min \tag{1}$$

Eq. (1) is user-defined expandable (eq. (2)).

$$\mu_D(x) = \mu_{G1}(x) \wedge \dots \wedge \mu_{Gn}(x) \wedge \mu_{C1}(x) \wedge \dots \wedge \mu_{Cm}(x) \tag{2}$$

For the case that certain quality criteria are not of equal importance transparent weighting of each individual quality criterion is possible. Especially weighting with multipliers λ_i, $0 < \lambda_I \leq 1$ in connection with the min-operator is a particular transparent way to implement the weighted AND-connection (Bernard et al, 2001). Since mathematically there is no distinction between fuzzy goals and fuzzy restrictions fuzzy quality criteria can be generally denoted by $\mu_i(x)$. The smaller λ_i is chosen, the more $\mu_i(x)$ will be emphasized. The ratio λ_i/λ_k represents the relative importance of two quality criteria μ_i, μ_k. For $\lambda_i/\lambda_k \rightarrow 0$ criterion μ_i is much more emphasised than μ_k.

$$\mu_D(x) = \lambda_1\mu_1(x) \wedge \ \ldots \ \wedge \ \lambda_n\mu_n(x), \qquad 0 < \lambda_i \leq 1, \wedge = \min \tag{3}$$

A correction term in eq. (3) is necessary to distinguish ranges with constant degree of membership in one or several quality criteria μ_i. This leads to eq. (4).

$$\mu_D(x) = \lambda_1\mu_1(x) \wedge \ \ldots \ \wedge \ \lambda_n\mu_n(x) + \varepsilon\mu_1(x)\mathrm{H}\ldots\mathrm{H}\mu_n(x), \qquad 0 < \lambda_i \leq 1, \wedge = \min \tag{4}$$

The optimal decision x* is calculated by maximising $\mu_D(x)$, where x is an element in the set of possible solutions X (eq. (5)).

$$\mu_D(x^*) = \max_{x \in X} \mu_D(x) \tag{5}$$

Quality criteria that yield to zero cannot be part of the optimal decision x*. This underlying expert knowledge leads to a practise-oriented range of solutions and reduces the computational effort. Nevertheless the solution will be Pareto optimal (Bernard et al. 2001). Figure 4 illustrates the concept of FDM for MCO and process control.

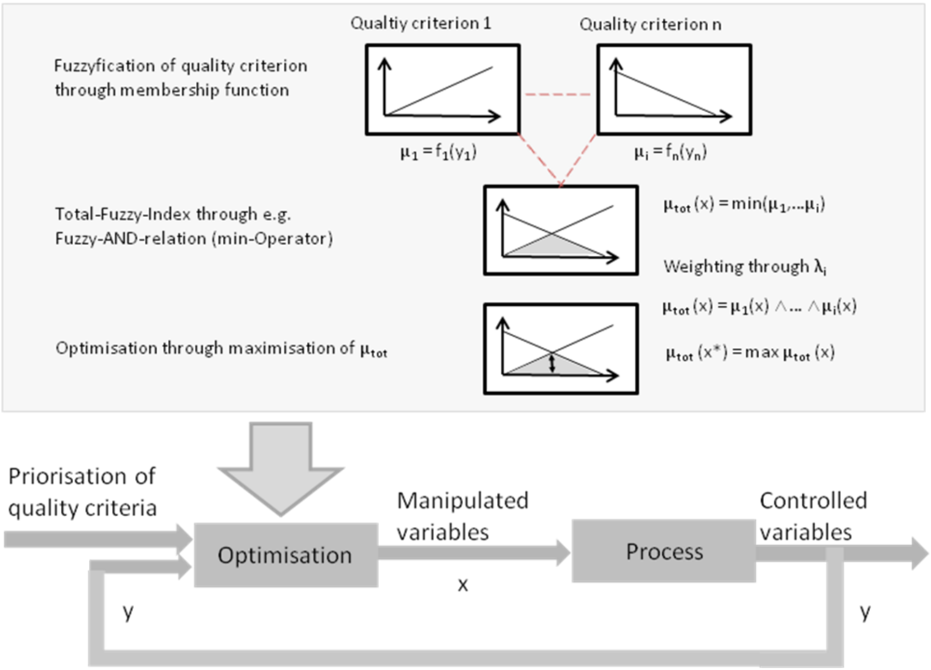

Figure 4. Fuzzy decision making for multi-criteria optimization

The "Haute-Sûre" wastewater system

The "Haute-Sûre" storage lake situated in the north of Luxembourg serves 70% of the Luxembourg population with drinking water. Its protection is therefore of national interest. The wastewater of the 25 surrounding villages will be drained to the newly built central WWTP Heiderscheidergrund. The predominantly combined sewer network that is currently under construction has a total length of 60 km with 60 % of pressure pipes. The sewer network comprises 24 first flush retention tanks with CSO structures with a total volume of 3050 m^3 and 25 pumping stations (see Figure 5). The rural catchment is predominantly characterised by agricultural use. The total impervious area is about 200 ha with a canalised area of 380 ha. Domestic and farm discharges equal 6,400 population equivalents (PE) in winter and because of tourist presence 12,000 PE in summer. A detailed description of the catchment is given in Henry et al (2007). The sewer network is qualified for real-time control for several reasons:

- It is situated in a widespread area. The discharge behaviour is inhomogeneous.

- There are several receiving waters with different sensitivity (see Table 1).
- Several control devices are situated within the system.

Beside a classic rule-based approach for real-time control of this sewer network (Henry et al, 2007) Fiorelli and Schutz (2009) describe a mathematical model for the minimisation of CSO during rain events based on model predictive control theory. A multi-goal objective function is used for on-line mathematical optimization of three weighted subgoals:

- Homogenous distribution of the first flush tank storage volume,
- Constant inflow to the WWTP,
- Minimisation of the CSO volume,

based on the tank volumes and the average transport times from each basin to the treatment plant (see Figure 5). Thereby transport phenomena within the sewer network are modelled as linear functions based on a pure-time delay model. Average transport times are calculated with Infoworks^{TM} CS based on hydrodynamic flow modelling.

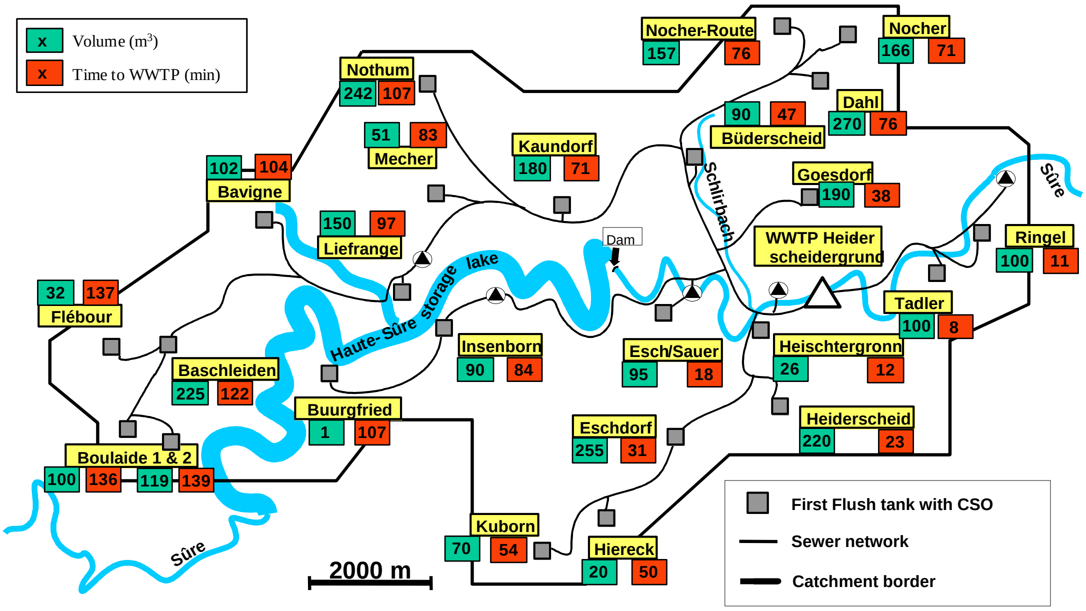

Figure 5. The ultimate Haute-Sûre wastewater system

The newly built WWTP Heiderscheidergrund is situated downstream the "Haute-Sûre" storage lake (see Figure 5). It is an activated sludge type facility with simultaneous nitrification/denitrification and biological/chemical phosphate removal. Final clarification is done by optional sand filtration, UV-disinfection and lagoons. Because of the seasonally varying loads the treatment plant will be operated during summer with 2 lanes and during winter with only one lane.

The simulation model

For integrated modelling of the "Haute-Sûre" wastewater system models of the sewer system and the treatment plant are connected to each other. Because of its complexity the sensitivity of the several receiving waters is regarded indirectly through different receiving water classifications according to table 1. These classifications influence the weighting of the corresponding quality criteria. Compared to an extended immission-based model this quasi-immission-based approach significantly reduces the computational effort of the total model. The optimiser for the sewer model (Fiorelli and Schutz, 2009) is coupled to a hydrologic sewer sub-model including a pollution load model based on the Lagrange approach (Alex, 2007). In order to simplify the complexity of interfacing the sub-models SIMBA® Sewer has been chosen for sewer modelling since it is also based on MATLAB/Simulink®, which will also be the platform for the FDM-model. The WWTP sub-model is based on the Activated Sludge Model No. 2d (Henze et al, 1999) included in the SIMBA® simulation system. Using this integrated wastewater simulation system will minimise the well-known problem of software interfacing in integrated wastewater modelling (Muschalla et al, 2009) by providing established interfaces.

Table 1. Receiving waters

Receiving water	**Classification***	**CSO structure**
Haute-Sûre storage lake, Beiwenerbaach	3	Liefrange, Buurgfried, Insenborn, Bavigne
Bauschelbaach, Bellerbaach, Syrbaach, Birbaach, Dirbech, Ansebech, Millbech	2	Bauschelbusch, Böllerbuch, Flébour, Nothum, Kuborn, Hiereck, Eschdorf pumping station
Sûre, Méineschbaach, Nacherbaach/Wiltz, Fluesbech/Schalbech/Schlirbech, Delerbaach/Boukelzerbaach, Dickesbur/Heesbech	1	Esch/Sûre, Heiderscheider-grund, Tadler, Ringel, Kaundorf, Nocher, Nocher-Route, Dahl, Büderscheid, Goesdorf, Eschdorf, Heiderscheid

*Classification: 3 = very sensitive, 2 = sensitive, 1 = less sensitive

For the MCO the model of the integrated wastewater system has to be integrated into a parent model for FDM. To this end the MATLAB/Simulink® based Fuzzy Logic Toolbox® is used.

Research Tasks

The present research is based on the following research tasks:

1. Calibration and validation of the above described sub-models for the sewer system and the WWTP Heiderscheidergrund based on existing and dedicated measurement data:
   - On-line measurement data provided by on-line measurement devices of CSOs already in operation (hydraulic loads) and the WWTP (hydraulic loads and pollution loads/concentrations).
   - Off-line measurement data provided by periodically installed measuring and sampling devices at already existing CSOs (pollution loads/concentrations) and the WWTP (sludge compensation).
   - Information of rainfall provided by automatic rain gauges in Boulaide and Heiderscheidergrund supplemented by a rain gauge during the periodic measurement campaigns.
2. Integration of the sub-models.
3. Development and implementation of integrated predictive control strategies. Definition of cost functions for sewer and WWTP operation based on energy consumption.
4. Development and implementation of a parent model for MCO based on the presented FDM method. Choice of quality criteria to be optimised.
5. Analysis of the influence of the weights for different control strategies. Comparison of 3 different stages of optimization: i) no optimization, ii) optimal control only for the sewer network and iii) integrated optimal control for sewer network and WWTP.

RESULTS AND DISCUSSION

Previous work focused on the development of sub-models for the sewer system and the WWTP Heiderscheidergrund. The common system platform MATLAB/Simulink® provides good support for the integration of the hydrologic sewer model and its optimiser. Simulations of the optimised sewer network operation with constant flow to the WWTP (maximum capacity of 87.6 m^3/10min) already show good improvements compared to the initial steady state system. For instance, for a 2-day rain event (one big storm event with a return period of about one month followed by two low intensity rain events) shown in figure 6 the optimiser provides a reduction of 46% of the total CSO volume.

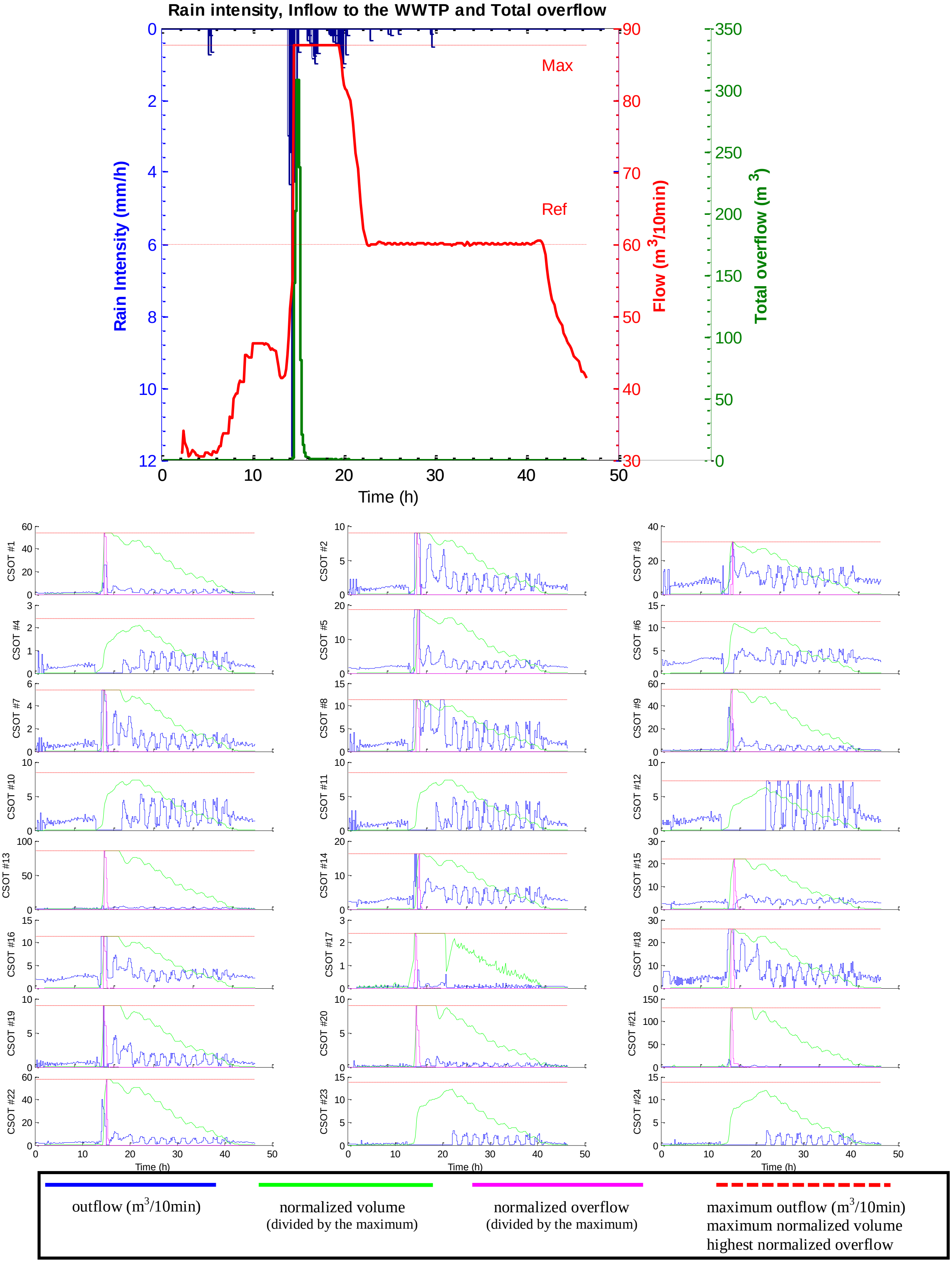

Figure 6. Example of operation during a realistic "heavy rain" with constant inflow to the WWTP

Thereby the optimiser is able to find the settings that reduce the total overflow of the uncontrolled sewer system from 1874 m^3 to 1016 m^3. The homogeneous distribution of storage volume is easily recognisable and achieved by continuous coordinated control of all pumps and throttles. Moreover, the minimised overflow is distributed according to the classification of receiving water sensitivities (table 1) and if possible prevented. Another simulation, now of one month, in which a rain event occurs with a return period of one year (26.75mm of precipitation during 26 minutes) shows a reduction of 13% in CSO volume (a decrease from 39665 m^3 to 34400 m^3).
The implementation into a hydrologic sewer network model thereby provides the following opportunities:

- Implementation of pollutant load modelling within the sewer network necessary for integrated modelling.
- Consideration of spatially distributed, "moving" and therefore more realistic rainfall events.
- The use of a common platform (MATLAB/Simulink®) is expected to also facilitate the integration of the sub-models for the sewer network and WWTP as well as the implementation of the parent model for the FDM.

Within the next step, integrated control/management of sewer network and WWTP will adapt the release from the CSO tanks to the actual capacity of the WWTP which is often higher than the commonly assumed double of the dry weather flow rate, as shown in many studies (e.g. Seggelke et al, 2005).

CONCLUSION

The study's goal is to investigate FDM for multi-objective optimization for the management of integrated wastewater systems. The expected outcome will therefore be a new mathematical tool to optimise the integrated operation of sewer networks and WWTP. Increasing multidisciplinarity in urban wastewater management leads to partially conflicting quality criteria. It is expected that FDM is an appropriate tool to solve such conflicts. The presented methodology of FDM for multi-criteria optimization has been successfully tested for non-linear and dynamic control systems (Bernard et al, 2001). In this particular case integrated cost functions will regard the balance of ecological and economical criteria showing a weighting in the sense of the goals of the European Water Framework Directive.

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