Integrated multi-criteria optimal model predictive control of a sewer network in a rural catchment

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Abstract
The potential for real-time control of combined sewer systems arises especially from the heterogeneous filling of retention tanks in a network connected to a central wastewater treatment plant (WWTP). Optimization can be achieved through homogeneous use of retention tank storage volume. The spatial variability of rainfall and uncertainties related to the estimation of catchment surfaces contributing to runoff from rainfall cause a heterogeneous use of storage volume available in sewer network retention tanks. This heterogeneity increases with the size and the number of sub-catchments. Due to this, combined sewer overflow seldom occurs simultaneously at all retention tanks within one sewer network but only at a few, while a non-negligible percentage of storage volume at retention tanks stays unused during wet weather. Real-time control and especially model predictive control is known to maximize the use of retention tank storage volume during combined wet weather flow. Multiple objectives related to the WWTP capacity and its homogeneous loading during combined wet weather flow or different receiving water sensitivities are often in conflict with the homogeneous use of storage volume at retention tanks and consequently in conflict with combined sewer overflow minimization. Consequently, the multi-criteria optimized operation of a combined sewer network is a compromise according to the specifications of each operator. The present study illustrates these compromises during real-time control of a rural combined sewer network. Thanks to multi-criteria optimization and integrated objectives the approach explains why retention tank storage volume is used incompletely during combined sewer overflow despite model predictive control. This is achieved by replacing the conventional objective function in model predictive control by a function for fuzzy decision-making for multi-criteria optimization. The results of the fuzzy decision-making within this fuzzy predictive control approach explain the reduction of pollution loads during unavoidable combined sewer overflow thanks to model predictive control.

Keywords
Combined sewer overflow, fuzzy decision-making, integrated control, model predictive control, multi-criteria optimization, real-time control

INTRODUCTION

Sewer network real-time control is proven to reduce combined sewer overflow (CSO) volume and loads thanks to the improved usage of storage capacities. Installations worldwide, especially in large urban systems have proven their efficiency. Colas et al. (2004) provide an overview on systems in operation. Recent implementations are reported for instance by Fradet et al. (2010) for the city of Montreal, Grum et al. (2011) for the city of Copenhagen or Fiorelli et al. (2013) for the Haute-Sûre network in Luxembourg. Approaches can be generally classified into rule-based and model-predictive approaches. Especially model-predictive control (MPC) approaches can adapt to the spatial and temporal variability of different rain events. Despite their proven efficiency the number of real-world MPC implementations compared to the number of scientific publications is rather small. Schütze et al. (2004) explain this missing acceptance of real-time control and especially MPC of sewer networks by the complexity and lacking transparency of such approaches. From lessons learned Schütze et al. (2004) deduce that the acceptance among sewer network operators can be increased if the ultimate control decision remains with operators themselves instead of computers using e.g. control assistance systems or operator-in-the-loop-approaches. This aloofness makes sewer network MPC implementations in rural catchments even rarer. Nevertheless, the implementation of a sewer network MPC approach in a rural catchment in Luxembourg shows promising results (Fiorelli et al., 2013). The present study shows the results of an alternative approach to incorporate fuzzy decision-making (FDM) into a MPC approach for integrated sewer network RTC in order to respect the objectives and constraints of the sewer network and WWTP operator for the multi-objective optimal control of a sewer network during combined wet weather flow (CWWF).

METHODOLOGY

Fuzzy decision-making

Fuzzy decision-making (FDM) is a mathematical approach to model decision-making according to human expert knowledge based on principles of fuzzy logic as introduced by Bellman and Zadeh (1970). Thereby, fuzzy membership functions μ_i for each objective variable and corresponding domain describe the degree of preference within the decision-making process ranging between 0 for total rejection and 1 for total preference (Figure 1). Multi-objective decision-making is modeled according to the aggregation of all fuzzy objectives consisting of goals and constraints, e.g. using the fuzzy-AND-relation which corresponds to the MIN-operator. Mathematically, the optimal compromise between conflicting objectives is found according to the maximum of the aggregated fuzzy membership function μ_{tot}. Figure 1 illustrates the general approach of FDM. Details on common membership functions for the fuzzyfication of objectives or fuzzy aggregation functions are given, e.g. by Regneri (2014).

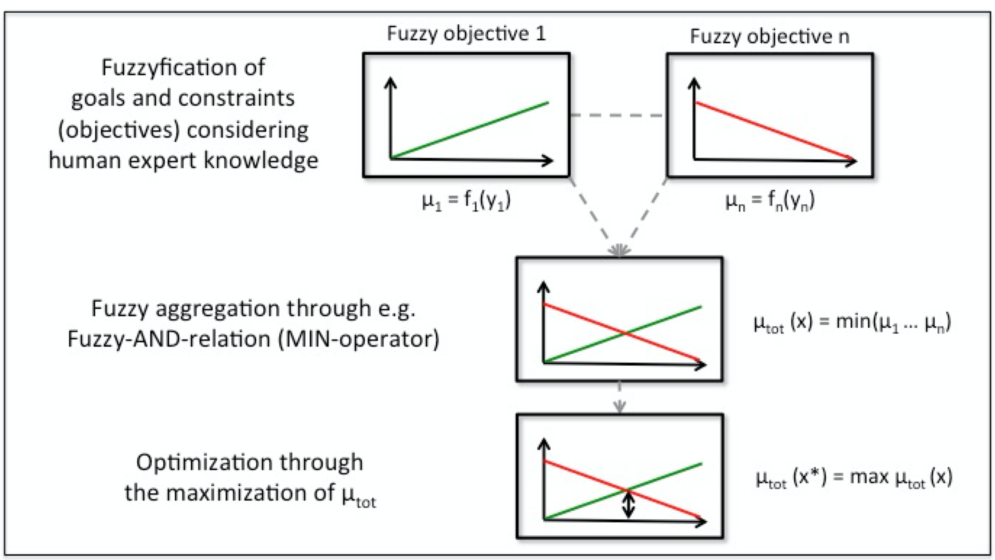

Figure 1. Mathematical description of fuzzy decision-making of conflicting objectives according to the aggregation of goals and constraints

Fuzzy predictive control of sewer networks

In MPC decision-making in multi-objective optimization is usually done by weighting specific objectives according to an offline analysis of Pareto optimal results. Fiorelli et al. (2013) illustrate the approach for sewer network MPC. In order to analyze optimal decision-making according to specific criteria FDM is used to replace the objective function in MPC in the present study. Figure 2 illustrates the corresponding general implementation of FDM within MPC for fuzzy predictive control (FPC). In sewer network MPC objectives can be, for instance, the minimization of CSO volumes or CSO loads; examples for constraints can be, for instance, the capacity of the WWTP or other hydraulic constraints in the sewer network.

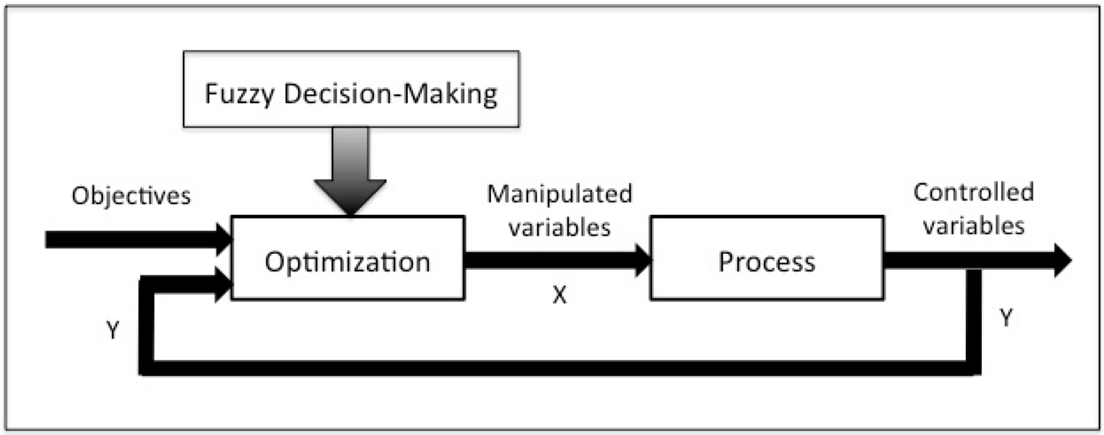

Figure 2. Implementation of FDM in MPC for FPC

Table 1. Linguistic description of objectives for the system-wide analysis and control of integrated rural sewer networks

No.	Description
1*	Minimize the total CSO volume at retention tanks in the sewer network
2	Minimize the total CSO COD load at retention tanks in the sewer network
3	Minimize the total CSO TKN load at retention tanks in the sewer network
4*	Minimize the total CWWF volume in all retention tanks for fast emptying
5	Homogenize the use of all retention tanks
6*	Minimize the emergency CSO volume at the WWTP
7*	Harmonize the inflow to the WWTP
8*	Maximize the flow to the WWTP along the interceptor sewer network (ISN) according to the reference value
9*	Harmonize the flow to the WWTP along the ISN according to the reference value
10*	Maximize the hydraulic load to the WWTP according to the current treatment capacity
11	Maximize the COD load to the WWTP according to the current treatment capacity
12	Maximize the TKN load to the WWTP according to the current treatment capacity

* used for FPC

Table 1 lists the linguistic description of the objectives for RTC of integrated rural sewer systems investigated in the present study. Objectives 1 to 3 are used to minimize CSO hydraulic and pollution loads. Objective 4 forces a quick emptying of all retention tanks. Objective 5 equalizes the use of retention tank storage capacities in order to minimize CSO. Objectives 6 to 12 optimize the flow and load to the WWTP from an integrated point of view. Table 2 summarizes the description of those objectives into fuzzy membership functions (MF) used to fuzzify the corresponding variables.

Table 2. Membership function (MF) description of objectives for integrated sewer network FPC

MF	Parameters	Variable	Explanation
1*	a = 0 m = 0 b = $\Sigma V_{in,RT,i}$	$\Sigma V_{over,RT,i}$	x is the sum of CSO volumes at all retention tanks. b is the inflow to all retention tanks.
2	a = 0 m = 0 b = $\Sigma L_{COD,in,RT,i}$	$\Sigma L_{COD,over,RT,i}$	x is the sum of CSO COD load at all retention tanks. b is the inflow COD load to all retention tanks.
3	a = 0 m = 0 b = $\Sigma L_{TKN,in,RT,i}$	$\Sigma L_{TKN,over,RT,i}$	x is the sum of CSO TKN load at all retention tanks. b is the inflow TKN load to all retention tanks.
4*	a = 0 m = 0 b = 24	$\sum f_{Vol,i}$	Filling degrees of retention tanks range between 0 and 1. b = 24 represents the total filling of all retention tanks. x is the sum of all filling degrees.
5	a = 0 m = 0 b = 0.5	$STD(f_{Vol,i})$	Filling degrees of retention tanks range between 0 and 1. b = 0.5 represents the maximum standard deviation. x is the sum of all filling degrees.
6*	a = 0 m = 0 b = 0	$V_{over,WWTP}$	The WWTP inlet has an emergency CSO structure. In order to avoid emergency CSO b is set to 0. x is the CSO volume at the WWTP.
7*	a = 0 m = 0 b = $MEAN(Q_{in,WWTP})$	$STD(Q_{in,WWTP})$	b is the mean of the WWTP inflow hydrograph. x is the standard deviation of the WWTP inflow hydrograph.
8*	a = 0 m = 0 b = $Q_{ref,WWTP}$	$MAX(Q_{ISN})$	b is the reference inflow to the WWTP describing its current treatment capacity. x is the peak discharge in the ISN.
9*	a = 0 m = 0 b = $Q_{ref,WWTP}$	$MEAN(Q_{ISN})$	b is the reference inflow to the WWTP describing its current treatment capacity. x is the mean discharge in the ISN.
10*	a = 0 m = $V_{in,ref,WWTP}$ b = $V_{in,ref,WWTP}$	$V_{in,WWTP}$	b and m are equal to the treatable reference volume. x is the volume to be treated.
11	a = 0 m = $L_{COD,in,ref,WWTP}$ b = $L_{COD,in,ref,WWTP}$	$L_{COD,in,WWTP}$	b and m are equal to the treatable reference COD load. x is the COD load to be treated.
12	a = 0 m = $L_{TKN,in,ref,WWTP}$ b = $L_{TKN,in,ref,WWTP}$	$L_{TKN,in,WWTP}$	b and m are equal to the treatable reference COD load. x is the COD load to be treated.

* used for FPC

The parameters a and b in the membership function describe the left resp. right boarders of triangular membership functions and the parameter m describes the peak of each triangular membership function used for the fuzzyfication of each objective. Equation (1) describes the aggregation of the objectives chosen for multi-criteria decision-making in FPC (marked with an asterisk in Table 2) into a total membership function MF_{tot} with the objective to be minimized.

$$MF_{tot} = (1 - MF_1) + (1 - MF_4) + (1 - MF_6) + (1 - MF_7) + (1 - MF_8) + (1 - MF_9) + (1 - MF_{10}) \quad (1)$$

with:
MF_i = membership functions

The rest of the presented objectives are investigated within the process of FDM with respect to their degree of conflict concerning the objectives chosen for FPC. This restriction was necessary due to the degrees of freedom in the case study which has 24 retention tanks with pumps or throttles and a chosen control step size of 10 minutes. Further details on the design of the chosen objectives and their membership functions for MPC of integrated rural sewer systems can be found in Regneri (2014). SIMBA Sewer was used to implement the simulation model in MATLAB Simulink. The sewer network prediction model considers constant flow times to the WWTP in the range of 10 to 120 minutes, complete mixing in retention tanks and constant inflow to each retention tank within a prediction horizon of 10 minutes. The inflow to each retention tank is derived from the measurement of throttled discharges and water levels. Regneri (2014) provides further details about the simulation model, the prediction model and the FDM model that was based on the MATLAB Fuzzy Logic Toolbox.

RESULTS AND DISCUSSION

Decisions in sewer network model predictive control

Figure 3 shows the rainfall data of August 2011 measured at four rain gauges within the rural combined sewer network under investigation. Details on the spatial variability and the phenomenological approach to model the investigated variability of rainfall runoff is given in Regneri (2014).

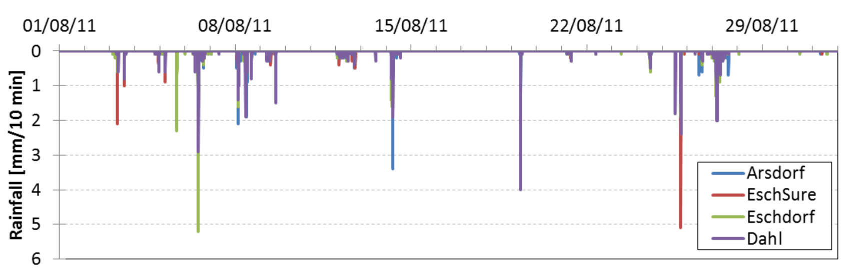

Figure 3. Rainfall time series for August 2011 in the case study catchment

Figure 4 illustrates the results of the FDM process for the CWWF event of 14/08/2011 with detail for each control step during this CWWF event. The results show that in the beginning of the event, when CSO cannot be avoided (MF1 resp. MF6), about 20% of the total retention tank volume remains unused (MF4) due to the objective to stabilize the flow to the WWTP and the insufficient retention tank volume at the WWTP for influent homogenization. The CSO at the WWTP (MF6) is thus kept smaller than the CSO in the catchment (MF1).

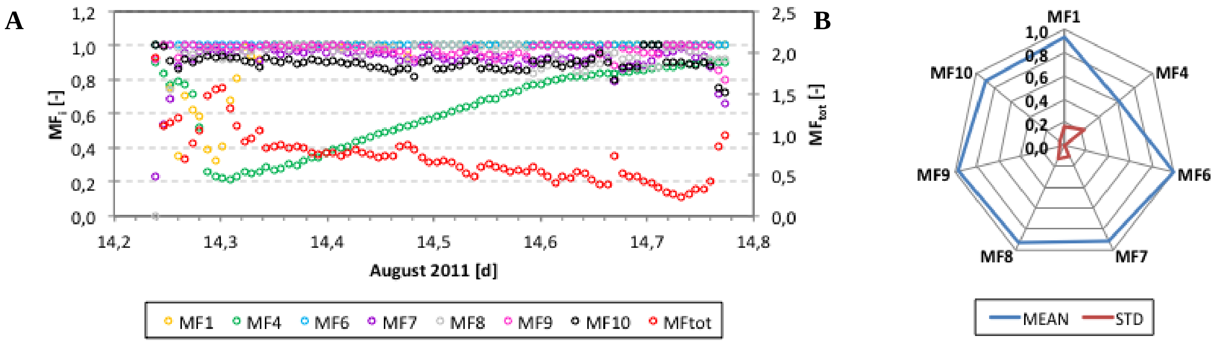

Figure 4. FDM results for sewer network MPC of CWWF event 14/08/2011 (A) and statistical evaluation according to membership function (MF) mean values and standard deviations (STD) (B)

Figure 5 illustrates the statistical evaluation of all five CWWF events. The comparison with figure 4 (B) shows a general agreement according to comparable mean values and standard deviations thanks to Pareto optimal solutions.

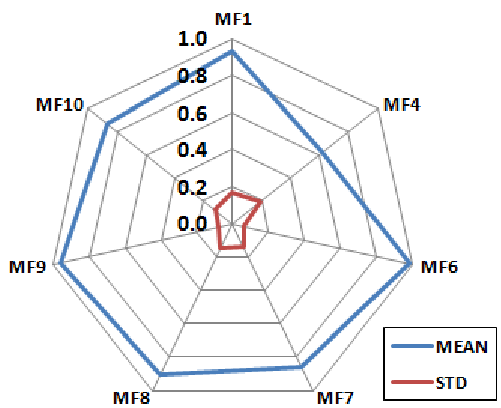

Figure 5. FDM mean results and STDs of 5 CWWF events according to the rainfall time series of August 2011 for sewer network control.

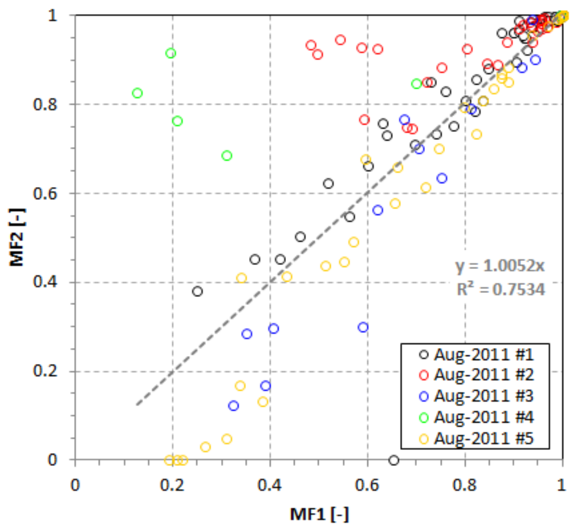

Figure 6. Correlation of MF results for total CSO volumes (MF1) and total COD CSO loads (MF2) for 5 CWWF events according to the rainfall time series of August 2011

Since pollution load objectives were not used within the multi-criteria optimization for FPC, only conflicts with hydraulic CSO objectives can be evaluated. The results for conflicts between hydraulic CSO objectives (MF1) and COD CSO objectives (MF2) are illustrated in Figure 6 for all five CWWF events of August 2011. The results principally show a linear correlation with a coefficient of determination of 0.75 indicating the need for pollution load objectives in sewer network RTC for pollution load minimization when CSOs cannot be avoided.

Partial least squares discriminant analysis (PLS-DA) was used to cluster the FDM results MF_i according to the simulated events of August 2011 #1 to #5 for the geometrical interpretation of density constant contours – ellipsoids according to Equation (2) (Regneri, 2014).

$$F = s_x \cdot s_y \cdot \sqrt{1 - r^2} \tag{2}$$

with:
F = area of the ellipsoid, s_x resp. s_y … center of gravity, r … radius

Figure 7 illustrates the conflict of (A) CSO minimization (MF1) and homogeneous WWTP loading (minimum of MF8 and MF9) and (B) retention tank usage homogenization (MF5) and homogeneous WWTP loading (minimum of MF8 and MF9). The overlap of the clustering ellipsoids demonstrates that for all five CWWF events the results for MF8 resp. MF9 are predominantly close for the rainfall time series August 2011. Results for MF1 only show slightly worse results. Due to the importance of the integrated performance of the whole wastewater system CSOs are allowed to happen in order to prevent the WWTP from failure (Regneri, 2014). Consequently, these overall objectives can be assumed to be satisfied. Conversely, the generally worse satisfaction of MF(5) which was not considered as objective function for the FPC illustrated in Figure 7(B) demonstrates the conflict with the homogeneous WWTP loading (MF8 and MF9) and this can therefore be assumed to be the primary cause for the unused retention tank storage volume that remains despite CSO.

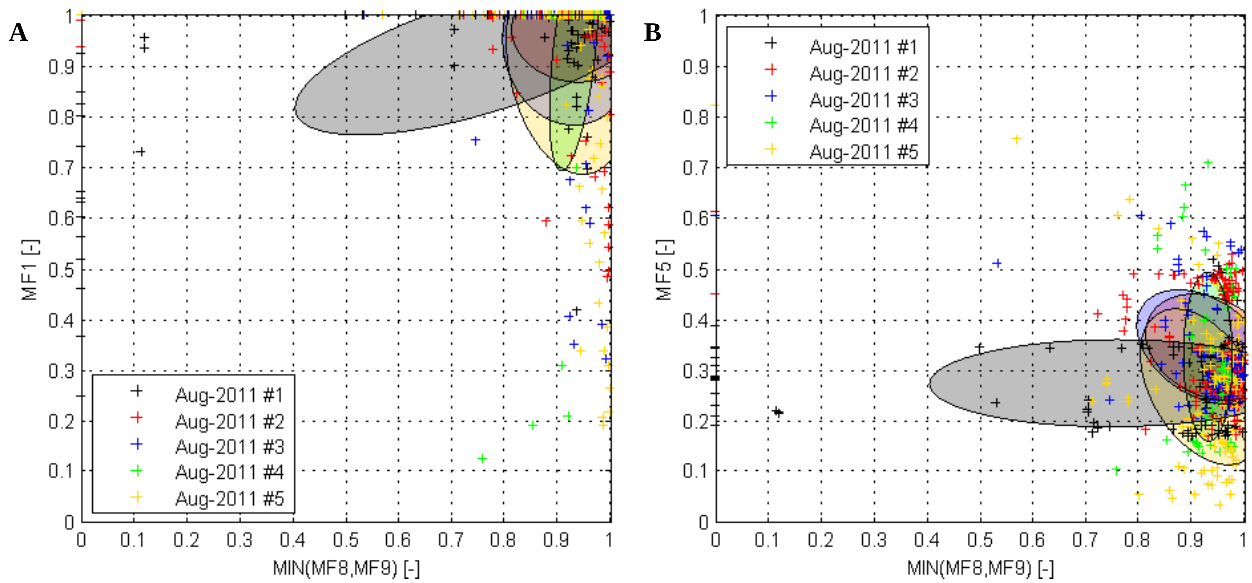

Figure 7. PLS-DA of MF results for ISN hydraulic homogenization (MF8 and MF9) and (A) CSO volume minimization (MF1) and (B) retention tank use homogenization (MF5) for 5 CWWF events according to the rainfall time series of August 2011

Performance evaluation

The performance of the FPC approach is compared to four reference scenarios with static sewer network control according to the chosen hydraulic WWTP loading representing four times the loading during dry weather flow (Ref1, 7200m^3/d), the design capacity of the WWTP (Ref2, 10680 m^3/d), the maximum capacity of the WWTP (Ref3, 12500 m^3/d) and a loading comparable to the average dynamic capacity comparable to the FPC of the WWTP (Ref4, 8490 m^3/d). Figure 8 shows the distribution of monthly CSO volumes and loads, and associated WWTP loadings during a month of average precipitation. In comparison to static sewer network control (Ref1 to Ref4) the approach shows a possible reduction of CSO volume of on average between 10 and 15% for the CWWF event of August 2011 compared to Ref1 and Ref2. Comparable CSO volumes are achieved while reducing the load to the WWTP. COD and NH_4-N reductions are comparable as well. The analyses of the results additionally illustrate the approach of multi-objective optimization within the FDM approach and the need to incorporate objectives that explicitly consider pollution loads in order to minimize these.

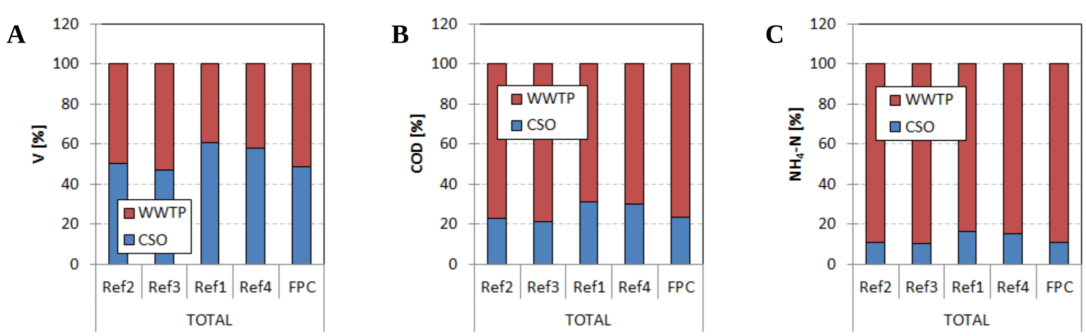

Figure 8. Comparison of CSO (A: volume; B: COD, C: NH_4-N) and the associated WWTP loading by fuzzy predictive control resp. static reference scenarios

Using a conventional convex MPC approach Fiorelli et al. (2013) confirm the present results concerning CSO volume reduction especially during heavy storm and strong rainfall events and indicate a mean annual CSO reduction of about 20%.

CONCLUSIONS AND RECOMMENDATIONS

The presented results for the FPC illustrate the dynamics of decision-making for multi-criteria optimal sewer network control along single events and the comparability of decision-making for different events according to the specific objectives of an integrated sewer network operator. In the case of insufficient retention tank storage volume at the WWTP the approach reveals the conflicts between homogeneous WWTP loading and unused retention tank capacity despite occurrence of CSOs. Adding extra retention tank volume at the WWTP for influent homogenization could increase the performance of the controller in the sense of CSO reduction. Future work should also consider homogenization of retention tank usage as objective in the FPC approach. The results of FDM also demonstrate the need of additional objectives that consider wastewater quality in order to minimize pollution loads in the case of unavoidable CSO. In comparison to uncontrolled sewer networks MPC reduces CSO pollution loads by delaying unavoidable CSO events thanks to dilution. FPC can be used both for the analysis of weak spots in the integrated design of sewer networks and as a practicable sewer network controller. One major advantage thereby is the transparent description of goals and constraints according to the specific demands of sewer network operators and their expert knowledge.

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