Control Strategy Tool for Sewer Networks

Description and Implementation

Expected CSO Risk

Minimize total expected CSO Risk in catchment by controlling Q.
COLOPHON

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Author(s)
Arne Møller (DHI), Nikolaj Mølbye (Krüger AS)

Quality Assurance
Anders Lynggaard-Jensen (DHI)

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1 Introduction

Real Time Control (RTC) of urban drainage system is increasingly applied to optimally exploit the existing storage network infrastructure. RTC is commonly applied to reduce Combined Sewer Overflows (CSO), improving the quality of receiving waters; to optimize flows to wastewater treatment plants; and to reduce floods in urban areas. The evolution of RTC methods requires the integration of modelling tools, sensors and data analysis approaches.

For the sewer network of the City of Aarhus a model based decision and control strategy tool is implemented that combines the major features of state-of-the-art RTC methods into a global generalized risk based approach. This approach allows a better management of the drainage system and the optimization of the existing infrastructures.

The tool is named DORA – Dynamic Overflow Risk Analysis – and is developed under the Storm and Wastewater Informatics project (http://www.swi.env.dtu.dk/), funded by the Danish Council for Strategic Reseach, Danish Wastewater Utilities, Universities and participating companies.

The DORA strategy seeks to minimize the total expected overflow risk in the main storage basins by considering (i) the water volume presently stored in basins in the sewer network, (ii) the maximum hydraulic capacities in the sewer network and the downstream WWTP, (iii) the expected runoff volume (calculated by radar-based rainfall forecast models), and (iii) the estimated uncertainty of the runoff forecasts.

In Aarhus, DORA is implemented on the DHI developed software platform DIMS.CORE, which at Aarhus Water is widely used as a monitoring and control platform (Figure 1.1).

![DORA implementation on the DIMS.CORE software platform](image)

*Figure 1.1: DORA implementation on the DIMS.CORE software platform*
The outputs from DORA are flowsetpoints for the gates and pumps controlling the flow from/to storage tanks in the sewer system.

1.1 Initial analysis

During the early phases of the project various simplified methods for deciding the flow in downstream direction from each storage tank was considered and tested. This work led to the conclusion that some optimization methodology was needed once the sewer network systems have several storage tanks and some locations with the possibility for diverting flow in various directions.

![Diagram of sewer network configuration](image)

*Figure 1.2: Simplified view of the sewer network configuration found in the City of Aarhus*

Figure 1.2 shows a simplified view of the sewer network configuration found in the City of Aarhus with seven main storage tanks a major pumping station (JP) and the receiving waste water treatment plant (MR).

The green arrows indicates the flows which can be controlled by operation of gates and pumps for regulating flow into the storage tanks and for emptying the tanks in downstream direction.

At each of the storage tanks there is also a location for Combined Sewer Overflow (CSO) which will be active if the capacity of the storage tank is fully utilized and the incoming flow exceeds the flow discharged in downstream direction. Otherwise there may be risk for local flooding within the catchment drained to the storage tank.

Depending on the receiving water the CSO locations are considered differently. If a CSO cannot be avoided then some locations are prioritised to be used before others. This adds to the complexity.
2 Optimization Methodology

2.1 Selecting optimization tool
The initial testing of simplified methods were implemented and executed as macro scripts in EXCEL. The optimization was tested by coupling the calculation in EXCEL with the hydraulic simulation model of the sewer network configured in the modelling tool MIKE URBAN.

The need for adding an optimization methodology was realized and search for a suitable algorithm resulted in selecting the ‘PIKAIA’ optimization tool. This is an implementation of a genetic algorithm (GA) for searching an optimal solution to the problem.

The PIKAIA optimization tool was available in an implementation written in the programming language BASIC. This implementation can be used both in EXCEL and in the scripting features in DIMS.CORE, which was foreseen to be the final implementation.

Description of PIKAIA tool implementing the GA can be found at this link: http://www.hao.ucar.edu/modeling/pikaia/pikaia.php

During the initial phase of the development there was a version of PIKAIA in BASIC language available at the above web-site. At the time of writing this report the web-site has changed. There is now a PIKAIA implementation in FORTRAN available.

2.2 Development version based on Excel and MIKE URBAN modelling
The research and development work continued for some time with the combination of EXCEL and execution of simulations with the MIKE URBAN model of the network.

Figure 2.1: Concept for executing the optimization method in Excel during development
2.3 Operational implementation with DIMS.CORE
The method was then transferred from Excel to an implementation in DIMS.CORE where the optimization method is used in real operation with input from sensors in the sewer network and current rainfall data delivered from the local weather radar system, LAWR, operated by the Water Utility at the City of Aarhus. The resulting optimized flow set-points are delivered to Global Variables and time series in DIMS.CORE.

![Figure 2.2: Concept for executing optimization method in real operation](image)

The global control for the operation of the sewer network has 3-4 levels of control. If some sensors are not available or other error situations like missing communication occurs then the operation falls back to a secure but less advanced operation based on less available information.

With all information available and data validated to have good quality the operation will apply the results from the optimization. That is the flow set-points for the downstream discharge for each of the storage tanks. In this mode of operation the control algorithms implemented in DIMS.CORE will send set-points to the SCADA system for the final operation of the controllable devices like gates and pumps.

2.4 Execution of the optimization method
The application of optimization methods like the Genetic Algorithm (GA) and other similar techniques rely on testing a very high number of possible solutions to the problem in a short time. The solutions are ranked by testing each solution against a fitness-function. The solution with the best result is then selected as optimal for the current input conditions.

Construction of the fitness-function for the problem which should be optimized is important. For the optimization of the operation of the storage tanks in the system applied for the City of Aarhus the development of the fitness-function is described in chapter 3.
In addition to computing the “cost” for each of the solutions suggested from the GA it is also possible and needed to check the solution against a set of “constraints”. An example of a constraint is the limited flow capacity of the sewer pipeline downstream of the two storage tanks ‘MV1’ and ‘MV2’ (figure 2.3). All solution suggested by the GA where sum of the flow from these two tanks exceeds the flow limitation (constraint) will be rejected as possible solutions.

Only the suggested solutions which fulfil all defined constraints will finally be ranked, and the optimal solution is selected based on the result from the fitness-function.

There are a number of parameters controlling the execution of the optimization using the GA. During the development various set of parameters were tested. In the final setup transferred to the operational system the execution of the GA results in 20300 suggested solutions. Where each solution is the set of flow values to be applied as the downstream flow for each storage tank. The testing against the defined constraints significantly reduces the number of acceptable solutions.

The definition and use of constraints must be evaluated carefully. If the number of acceptable solutions among the suggested solutions becomes too low the methodology becomes less reliable and the constraints and the parameters for the execution of the GA must be re-considered.
In the implementation of the optimization method in DIMS.CORE the execution is continuously monitored and a number of parameters are extracted from each execution and stored as time series in the DIMS.CORE database (figure 2.4-28). This allows for manual inspection of the performance of the optimization for past events. It also allows for a continuous monitoring of the optimization method which then can be rejected as the basis for the active control, if the criteria for acceptance are not met.

The individual constraints get accepted in a varying number of solutions depending on the actual conditions in the sewer network and depending on the distribution of forecasted rain fall and other conditions.

![Figure 2.5: Example - number of solutions where three applied constraints get accepted and the final total accepted solutions (blue graph)](image)

Figure 2.5 shows the number of solutions accepted by each of three applied constraints. The final number of solutions represents those solutions where all three applied constraints are accepted within the same solution.

![Figure 2.6: Results from 20300 executions of GA](image)
Among the accepted solutions from the GA the optimal solution is selected. This solution is found by testing the solution with the implemented ‘fitness-function’ (FF) and selecting the solution producing the best result from the FF (Figure 2.9). Figure 2.6 shows the complete set of 20300 results from FF for one GA execution. It is seen that the GA itself uses the result from FF in the attempt to find combination of flow values which can improve the result from FF. The execution of the GA is represented by the x-axis. First tries to the left and last to the right.

![Figure 2.7: Results from 20300 executions of GA – zoomed to final optimized result](image)

The GA execution example presented in figures 2.6 and 2.7 resulted in a total of 89 consecutive improvements of the optimized result. For each of these solutions the resulting flow for each downstream connection is shown in the next graph.

![Figure 2.8: Resulting flows approaching an optimal solution](image)
Figure 2.8 shows a high variation in the resulting flows within the first suggested solutions. When more solutions get tested, the resulting flow values approach the final solution selected by the optimized result from the FF.

The execution of the GA optimization is shown schematically in figure 2.9. Internally, the algorithm optimizes the solutions to relative values in the range [0 .. 1.0]. To obtain the flow values, the solution is scaled to the flow range currently allowed for each downstream connection. The Qmax values are found based on the current water level conditions in the sewer network.

The cost calculation made in the fitness-function uses the information about the predicted rain fall and dry weather flow (waste water) and the current filling of the storage tanks.

Genetic algorithm - Optimize ”R”

![Diagram](image-url)

Figure 2.9: Execution sequence of the optimisation using the GA

The execution time for the complete optimization cycle is approx. 120 sec for the system in operation at the City of Aarhus. This includes optimization for two areas: ‘Marselisborg’ with seven storage tanks and ‘AabyViby’ with three storage tanks. This performance is acceptable within the general control system heart beat which has been set to 5 minutes for the control loop. Sensor data sampling frequency is one minute.
3 Dynamic Risk Overflow Analysis

This chapter includes the basic details from the technical documentation of DORA – “A New Generalized Dynamic Overflow Risk Assessment strategy (DORA) for Real Time Control of urban drainage networks”. For full technical details regarding DORA, visit http://www.swi.env.dtu.dk/.

DORA is the central function evaluating possible solutions from the GA (as shown in figure 2.9) in order to minimize the total expected overflow risk in the main storage tanks by considering:

- Wastewater volume presently stored in tanks in the sewer network
- Maximum hydraulic capacities in the sewer network and at the WWTP,
- Expected runoff volume (calculated by radar-based rainfall forecast models)
- Estimated uncertainty of the runoff forecasts.

The calculations done in DORA is based on a generalised simplified model of a sewer network as shown in figure 3.1, (an actual implemented simplified model is shown in 1.2). It consists of:

- Storage tank volumes
- Connections between storage tanks
- Reduced catchment area for each storage tank
- A downstream boundary – mostly implemented as the actual maximum hydraulic capacity at the wastewater treatment plant

Figure 3.1: DORA is based on a generalised simplified model of a sewer network
By running the DORA model in the optimisation framework as described in the previous chapter several thousand combinations of flow in the connections are evaluated. The output from the optimisation is the combination of flows giving the lowest total CSO risk. This combination is therefore chosen as setpoints for the flow in the connections.

3.1 Overview of the input to DORA
The execution of the optimisation relies on real time data coming from various parts of the monitoring system implemented on the DIMS.CORE platform

3.1.1 Wastewater volume presently stored in tanks in the sewer network
One of the key parameters in DORA is the wastewater already stored in the actual basin, \( V_w \). This is one of several parameters in the model – figure 3.2. The volumes already stored in the tanks are derived from level measurements in the tanks.

![Figure 3.2. Input of the actual use of the storage tanks](image)

3.1.2 Maximum hydraulic capacities in the sewer network and at the WWTP
In order to suggest a transport of wastewater from one basin to another, it is necessary to know the actual maximum hydraulic capacities in the pipes connecting the storage tanks, \( Q_{\text{max}} \).

![Figure 3.3: Input of maximum hydraulic capacities](image)

\( Q_{\text{max}} \) values are calculated from online measurements in the sewer system taking into account any constraints caused by downstream (high) levels. In the sewer network in the City of Aarhus, level measurements are located at each connection. Based on these measurements, the necessary
flow parameters are calculated. Calculating $Q_{\text{max}}$ is carried out under strict conditions regarding allowable levels in the sewers. Thus no levels exceeding the top of the sewer pipes are allowed.

The downstream boundary in the DORA model in Aarhus is defined as the actual maximum hydraulic capacity at the WWTP, $Q_{\text{biomax}}$. This parameter is calculated from online measurements at the WWTP.

3.1.3 Expected runoff volume (calculated by radar-based rainfall forecast models)

The expected runoff, $Q_F$, is based on a 1 hr. forecast estimate derived from radar rainfall measurements. These forecast estimates are used in linear reservoir models calculating the expected runoff volume for every storage tank in the coming hour. The expected runoff volume is defined as $V_F$ and is given when $Q_F$ is integrated within a certain time period. When $V_F$ is combined with $V_w$, the total hydraulic load on the basin is given – figure 3.4.

![Figure 3.4: Input of expected runoff volume](image)

3.2 Handling uncertainty in DORA

DORA operates within a certain time domain. $T_{cr}$, given by the time it takes for the total forecasted runoff volume to fill up all the storage tanks in the catchment. This time domain cannot exceed the length of the forecast horizon (1 hr.) Within this time a given volume of water is stored in the tank given by $T_{cr}*(Q_{in}-Q_{out})$, where $Q_{in}$ is water arriving from upstream tanks and $Q_{out}$ is water leaving to downstream tanks – figure 3.5.

![Figure 3.5: Critical time and critical volume](image)
The empty free volume left in the tank is defined as the critical volume, $V_{cr}$. This is the volume available for storage for the forecasted volume and the volume optimisation seeks to increase. When the critical volume is zero an overflow will occur.

The expected runoff volume derived from radar measurements and forecast calculations is associated with a certain degree of uncertainty in figure 3.6 (top) this is represented by the dotted lines on the QF plot. The runoff uncertainty is handled by using a gamma distribution describing the actual overflow probability. This is given by the red area in figure 3.6 (bottom) and is calculated by integrating the probability curve from $V_{cr}$ to $V_F$.

Further, each storage tank is given a specific cost factor reflecting the sensitivity of the receiving water body to where a CSO from the tank will flow. This cost factor is included in a linear cost function describing the actual overflow cost for each basin.

Risk is normally defined by probability multiplied by cost. This is also the case in DORA – and multiplying the probability formula and cost formula is shown in figure 3.7, where the overflow cost first is calculated by multiplying the CSO volume ($V_F - V_{cr}$) and the specific cost factor. The total CSO risk is given by $C_F$. Actually this can also be defined as the total CSO cost when integrating the formula from 0 to infinity instead of from $V_{cr}$ to infinity. The result is the same due to the fact that both the probability and the cost is 0 from $V_F = 0$ to $V_F = V_{cr}$.

The storage tank specific cost factor is one of the key parameters in setup of the optimisation as storage is favored in tanks with lower cost factors. This enables the operator to decide where an
unavoidable CSO should occur and thereby protecting the most sensitive receiving water bodies.

![Figure 3.7: Calculating overflow probability, overflow cost and the total overflow risk](image)

### 3.3 The DORA cost function

The total overflow cost $C_F$ is the most important element in the cost function. However, it is only one out of four cost factors included in the cost function in Aarhus. The other three are (also shown in figure 3.8):

\[
Cost = \sum_{i=1}^{N_{basin}} \left( C_{cr,i} + C_{F,i} - C_{hor,i} - C_{dQ,i} \right)
\]

- Cost due to water already fallen in the catchment
- Cost due to forecasted runoff
- Discount accounting for qualitative uncertainty (we don’t know everything about the future)

![Figure 3.8: The DORA cost function as it is defined in the Aarhus configuration](image)
• $C_{cr}$ is cost due to water already fallen in the catchment, i.e. if overflow is occurring when DORA is running, the cost from this overflow volume should be included in the optimization.
• $C_{chor}$ is a cost discount included in order to account for the fact that we have no knowledge of the size of the runoff volume beyond the forecast horizon. Thus this factor rewards a higher degree of spare storage capacity in the basins. During rain events this factor has less value. During dry weather periods and especially when emptying the basins after a rain event, this factor gains a bigger significance.
• $C_{dQ}$ is a cost discount included to ensure stability of optimal flows in conditions of low overflow risk. In conditions of low overflow risk the DORA algorithm has a higher possibility of a larger variation in the estimated optimal flows.
4 Practical implementation

Every 5 minutes all necessary information is fed into the Dynamic Overflow Risk Analysis from the DIMS.CORE platform, i.e. every 5 minutes new setpoints are delivered to the sewer system from the optimisation. In order to execute the optimisation and produce the setpoints, all online communication linking PLCs, the SCADA system and the DIMS. CORE platform has to be working.

From the PLCs, level measurements are delivered to the SCADA system from where they are sent to the DIMS.CORE, which uses configured software sensors to produce the necessary information needed by the optimisation. The actual maximum hydraulic load from the wastewater treatment is delivered by a DIMS system at the WWTP (see also deliverables D4.5.1-D4.5.3).

Radar images (actual and forecasts of reflectivities) are delivered directly to DIMS.CORE from the weather radar system. The images are converted into rainfall intensities, and Mean Area Rainfall (MAR) are extracted for each catchment. The actual and forecasted MAR values are converted into runoff values for each catchment.

When the is finished, the setpoints are fed into a PID controller calculating the necessary output to the gates and pumps in the sewer system. These outputs are sent through the SCADA system to the PLCs. The calculation loop is shown in figure 4.1.

![Figure 4.1: Optimisation – DORA calculation loop runs every 5 minutes](image)

The setpoints sent to the PLCs are maintained by the PID controller in DIMS.CORE. Every minute the PID controller evaluates how far off the flow setpoints are from the actual calculated flow in the connections (sewer pipes), and adjusts the output accordingly – figure 4.2.
Figure 4.1: Set-point control – calculation loop runs every minute

In the DIMS.CORE software a user interface has been designed in order to give the operator the opportunity to investigate actual and historical data regarding the optimisation and control of the flows in the sewer network – figure 4.3.

Figure 4.3: User interface for the optimisation and control of the flows in the sewer network
The user interface contains an orthofoto of the actual area in Aarhus covered by this part of the optimisation and control – The Marselisborg WWTP catchment including the old city center (another user interface for the optimisation and control of the Aaby/Viby WWTP catchments has been done as well). Yellow squares on the photo symbolise the storage tanks and areas with different colours which symbolise the catchments for each storage tank.

Beside the orthofoto the actual DORA configuration is seen, i.e., how the different tanks are linked to each other. The storage tanks are given a height according to their specific volume (millimeters of rain on the catchment that fills the tank). Actual tank filling is shown in blue inside the tanks. The locations of the tanks are reflecting their actual placement in the real world.

A zoom into the user interface is shown in figure 4.4. Below each storage tank name (black bold letters) the specific cost factor for the actual tank is placed (red C). It is seen that for tank HB the cost factor is defined as a value of 10, and for tank TB as a value of 4. Thus the optimisation tends to decrease wastewater flowing from TB to HB and thereby minimizing the total CSO cost.

Figure 4.4: Zoom into the user interface for the optimisation and control of the flows in the sewer network
On each connection between the tanks, the actual flow, actual maximum allowed flow and the actual flow setpoints are reported in blue. Beside the tanks, actual specific tank parameters and values are shown in dark blue, such as the actual forecasted volume $V_F$, the actual critical volume $V_{cr}$ and the actual overflow volume $V_{ov}$. The actual calculated CSO cost, Calc. $C$, is shown in red.

The user interface is designed in order to also enable the operator to monitor historical data in an easy way. In figure 4.5 the blue square incircled in red has been activated resulting in a pop up graph showing historical data. This feature is possible with all the coloured circles and squares and covers data regarding both connections and tanks.

Figure 4.5: Monitoring of historical data.
5 Conclusion and recommendations

During development of the system some further improvements has been considered. The very schematised simplification of the sewer network used in the optimisation method cannot provide detailed information about consequences at various locations in the network when applying the flow set-points found by the algorithm.

More detailed result can be found by executing the MIKE URBAN model setup with the selected flow set-points as input to the RTC (Real Time Control) configuration in the model. Ideally this option might be used to evaluate the few highest ranked optimized solutions and finally decide the flow set-points based on this. Another option might be a comparison between continued operation without changes and the solution selected by the optimization.

Model simulations based on the detailed model in MIKE URBAN are being executed presently. These simulations are done for delivering data for the Bathing Water information and Warning system (deliverable D4.5.4). In this mode the model produces results for both the hydraulic conditions and for two Bacteria components. These simulations are completed in approx. 10 minutes for both model areas. The heart beat for the warning system is set to 15 minutes.

Therefore the use of more complex models for optimization of the control is no longer far from possible, and for this purpose the hydraulics modelling alone can be used. This will be faster than the simulations for the warning system where water quality components are included. Other performance optimisations and use of a dedicated powerful computer could open for the perspectives of predictive model-based control using a more complex model description.