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B. Beraud, M. Mourad, E. Soyeux, C. Lemoine, M. Lovera. Optimisation of sewer networks hydraulic behaviour during wet weather: coupling genetic algorithms with two sewer networks modelling tools. Novatech 2010 - 7ème Conférence internationale sur les techniques et stratégies durables pour la gestion des eaux urbaines par temps de pluie / 7th International Conference on sustainable techniques and strategies for urban water management, Jun 2010, Lyon, France. pp.1-10. <hal-03296533>

HAL Id: hal-03296533

<https://hal.science/hal-03296533v1>

Submitted on 22 Jul 2021

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Optimisation of sewer networks hydraulic behaviour during wet weather: coupling genetic algorithms with two sewer networks modelling tools

Optimisation du comportement hydraulique des réseaux d'assainissement par temps de pluie : couplage d'un algorithme génétique avec deux logiciels de modélisation

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RÉSUMÉ

Les gestionnaires des systèmes d'assainissement sont confrontés aujourd'hui à des problèmes d'optimisation relativement complexes. Le but est généralement de bénéficier de la capacité maximale de l'infrastructure existante ou de démontrer ses insuffisances. Cette étude présente une approche permettant de répondre à cette problématique. Elle est fondée sur le couplage entre une méthode d'optimisation multi-objectif largement approuvée (l'algorithme génétique NSGA-II) et les logiciels de simulation de réseaux d'assainissement tels que MOUSE et Infoworks CS utilisés ici. L'approche a été appliquée sur deux cas d'études : à Berlin sur une partie du système d'assainissement et à Kolding au Danemark sur le système entier. Certaines consignes de gestion des organes de régulation ont été considérées pour l'optimisation ainsi que deux pluies réelles locales par site d'application. Des performances légèrement meilleures ont été obtenues mais sans oublier que les consignes de gestion initiales sont issues d'une longue expérience dans la gestion de ses réseaux et d'études poussées de conception. L'approche semble donc prometteuse, tirant avantage d'un algorithme d'optimisation performant et de logiciels de modélisation puissants et complets.

ABSTRACT

Sewer systems managers are faced frequently to relatively complex optimisation problems. The objective is to take total advantage of the existing infrastructure or to reveal its shortcomings. This study presents an approach that allows engineers to overcome such problems. It's based on the coupling of the largely approved multi-objective optimisation algorithm (NSGA-II) with powerful sewer networks simulation tools such as MOUSE and Infoworks CS. This approach is applied on two case studies: on a part of the sewer system of Berlin and on the whole sewer system of the city of Kolding in Denmark. Relevant parameters of the control system and two real local rainfall events were considered for the optimisation for each case study. Slightly higher performances were found but one should keep in mind that initial controls have been set according to a long management experience and advanced design studies. Thus, the approach appears to be promising, taking advantage of a reliable and efficient optimisation algorithm and powerful well renowned modelling tools.

KEYWORDS

Genetic algorithms, hydraulic modelling, optimisation, real time control, sewer system

1 INTRODUCTION

Sewer systems managers frequently face optimisation problems for the design, operation and rehabilitation of sewer networks. Modelling tools offer the possibility to test and compare different control scenarios, set and designed with engineering good-sense and experience. However, sewer systems are becoming more complex and control devices are more numerous and interdependent. Hence, the number of possible control configurations and settings can be countless and the search for an optimal solution can become rapidly complicated. In such cases, engineering good-sense and experience may miss more interesting but less obvious solutions.

Advanced optimisation algorithms such as genetic algorithms are powerful tools to solve such problems since they can perform guided search for the optimal solutions. Many successful applications on many case studies are available in the literature (Rauch and Harremoës, 1999, Muschalla *et al.*, 2006, Guo *et al.*, Yang and Su, 2007, Fu *et al.*, 2008).

In this study, the focus is put on the optimisation of control strategies that have to be adapted by the managers to meet operational goals. The benefit of control strategies has been proved in many studies (Schütze *et al.*, 2004, Borsányi *et al.*, 2008) but a main critical problem against the adoption of control practices relates to the difficult adaptation to very different sewer topologies and varying wet weather conditions. On this aspect, optimisation objectives can be multiple and very disparate but minimization of overflows volumes and frequency are very recurrent ones. Existing optimisation attempts concerning the optimisation of control rules (Rauch and Harremoës, 1999, Muschalla *et al.*, 2006) mainly focused on the use of simplified models to consider the entire integrated sewer system representing the sewer network, the WWTP and the river. While this approach allows having more room for the optimisation, it may compromise the reliability of the optimisation results as simplified models can be expected to be less-capable when dealing with complex systems.

The optimisation technique used is the NSGA-II. It has already been successfully applied in many cases like the optimisation of WWTP control (Beraud *et al.*, 2007), of the sewer network design (Guo *et al.*, 2006) and of the control of integrated wastewater systems (Fu *et al.*, 2008). This optimisation technique is directly coupled with powerful modelling tools used for detailed simulation of sewer networks behaviour. Two case studies are carried out: i) one in Berlin, Germany, on a sewer network modelled with Infoworks CS with a focus on reducing critical overflows and ii) one in Kolding, Denmark, on a sewer network modelled with MOUSE Software with a focus on reducing overflows, and pumping energy while avoiding to cause any flooding.

2 METHODS

2.1 Case studies presentation

2.1.1 Berlin case study

The catchment used for this case study is known locally as the Berlin VIII catchment and has approximately 79,000 inhabitants. The combined flows produced by the catchment are directed to a main pumping station of Berlin sewer system. The wastewater collected in the main pumping stations is transported toward the three wastewater treatment plants of the Berlin area through pressure mains. Each of the main pumping stations is allocated a maximum pumping flow during wet weather allowing a better performance of the wastewater treatment plants.

The Infoworks CS model of this catchment was developed during the ISM project (Integrated Sewage Management in Berlin) carried out by the KWB (Kompetenzzentrum Wasser Berlin) between 2003 and 2006 (Schroeder *et al.*, 2004). The model have been used and updated by the BWB (Berliner Wasserbetriebe) subsequently.

The total area considered in the model is about 516 ha. 25 km of pipes, 21 weirs, 2 pumps and 2 sluices have been taken into account. This case study aims to optimise the control at the pumping station (Figure 1) in order to minimise the total volume of upstream overflows and the volume of the overflow at the storage tank with respect to the maximum allowable pumping flow toward the WWTP. The runtime for a one day simulation period ranged between 40 and 60 seconds (single core of a Xeon 3 GHz CPU).

The functioning of the pumping station can be described as follows:

- Pumping toward the WWTP is accomplished by a variable speed pump. The speed of the

pump depends upon the water level in the pumping tank with a maximum allowable flow toward the WWTP of 690 L/s. The pump works with five different pumping speeds;

- When the water entering the pumping tank exceeds the pumping capacity toward the WWTP and the water level within the tank reaches a defined threshold, pumping toward the storage tank is activated. A fixed speed pump with a capacity of 1000 L/s is used. The pump stops when the water reaches back a defined lower level in the pumping tank;
- The storage tank is equipped with a weir to evacuate the received over storage capacity flow;
- The storage tank is emptied with a controlled sluice depending also on the water level in the pumping tank.

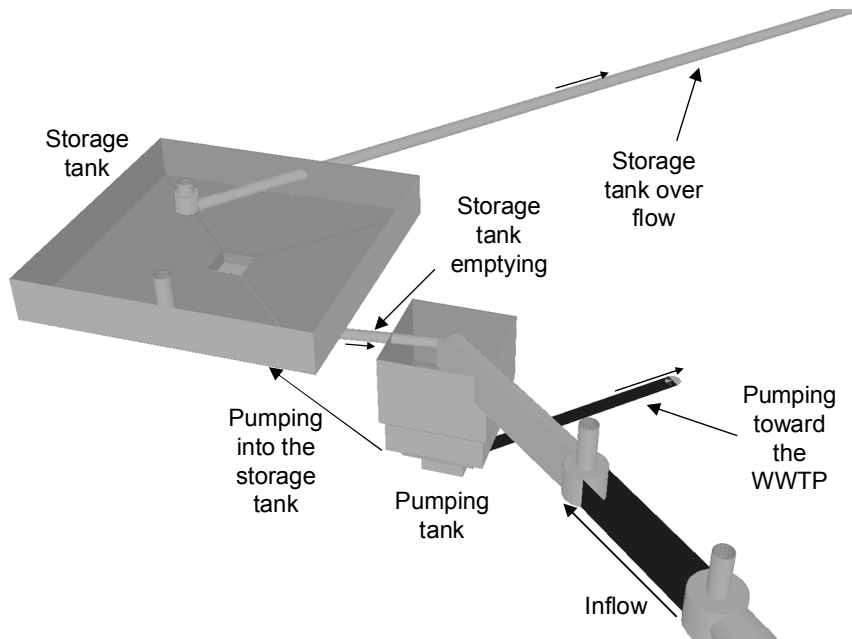


Figure 1. Sketch representation of the pumping station

Two rain events (Figure 2) suggested by BWB where considered for this case study with overflows occurring upstream in the network and at the storm water tank with the initial control configuration. The RB1 and RB2 rain events have respectively total depths of 22 and 30 mm.

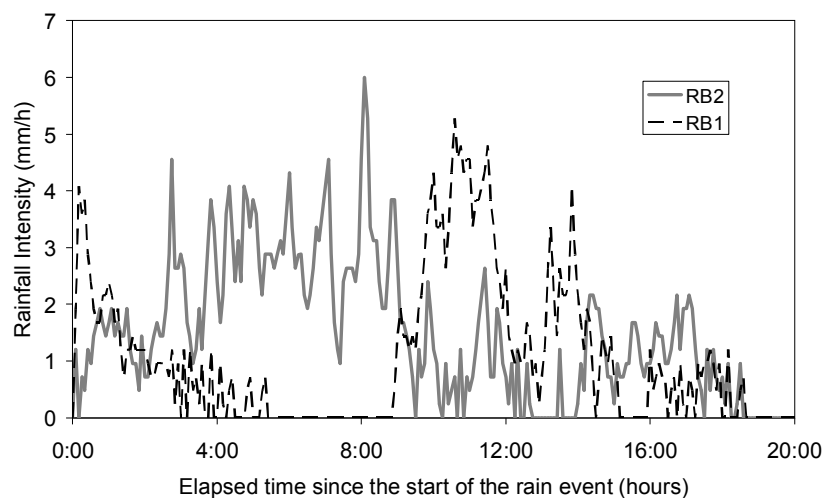


Figure 2. The two rain events considered in the optimisations for the Berlin case study

8 variables were considered for optimisation:

- 4 water levels controlling the variable speed pump;
- 2 water levels controlling the fixed pump (switch on level/switch off level);
- 2 water levels controlling the emptying sluice (open level/close level).

Operational constraints have been taken into account. Minimum difference between two successive control levels was set to 10 cm to prevent highly dynamic functioning of control devices.

2.1.2 Kolding case study

Kolding is a Danish city of approximately 86,000 inhabitants. The central part of the city catchment is drained by a combined sewer system, witnessing occasionally sewer overflows (CSOs) during rain events. Extreme rain events have even caused floods in the past, due to surface runoff and sewer overload. A current work by Krüger (Høegh Nielsen *et al.*, 2009) concerns the implementation of a control strategy for the limitation of these events (CSOs and floods).

For the implementation of the control strategy, a model of the sewer system has been developed using the MOUSE software from DHI. This whole model is presented in the left part of Figure 3. It is composed of 4794 catchments, 7136 manholes, 58 basins, 65 outlets, 94 weirs, 76 pumps, 16 gates and 7231 pipes. The simulation of one day network operation requires 29 minutes of computation on a modern CPU (single core of a Xeon 3 GHz). If this computing time may be reasonable for manual tuning of the controls, it is however not realistic for use in automatic optimisation.

A simplified structural model has hence been computed for the purpose of the optimisation. This simplified model has been achieved by trimming, merging and pruning the model while conserving volume, transport times and catchments (Leitão *et al.*, 2009). The simplified model is composed of 729 catchments, 1170 manholes, 58 basins, 65 outlets, 94 weirs, 76 pumps, 16 gates and 1241 pipes. With this reduced model, one simulation day takes around 4 minutes of computation on the same CPU.

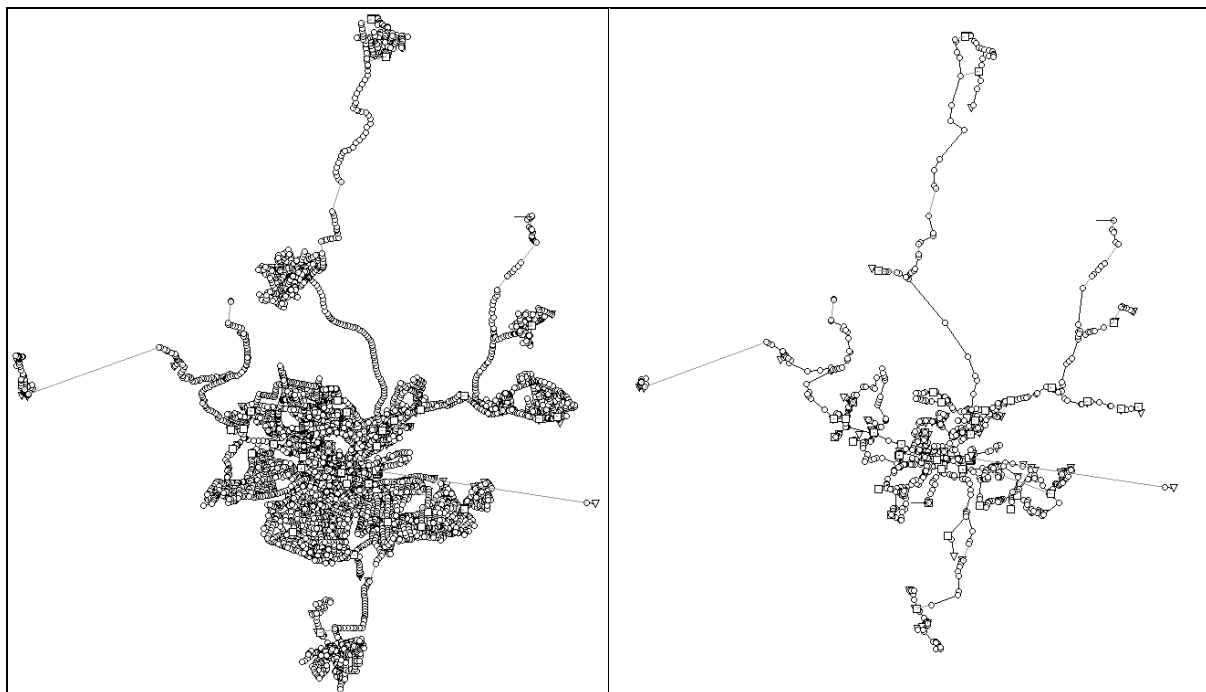


Figure 3. The complete (left) and simplified (right) models of Kolding sewer network

The optimisation performed on this case study aimed to minimise the CSOs volume and pumping energy. The CSOs total volume is directly computed from the simulation results. Since the efficiencies of the pumps are not known, the pumping energy is estimated by the potential energy given to the water during the simulation as shown in Eq. 1 below, where $Q(t)$ is the water flow rate and $\Delta h(t)$ is the difference of water height between outlet and inlet of the pump (positive when outlet is above inlet).

$$PumpingEnergy = \int_0^T Q(t) \cdot \Delta h(t) dt . \quad (1)$$

In order to minimise these objectives, 18 variables have been identified in the network control as most sensitive ones. They concern the operation of the pumps to the WWTP and the filling/emptying of five major storage basins. Relevant bounds have been identified for each of them. These variables will have to be adjusted by the optimisation algorithm for best performances. Constraints are also added concerning the fact that no flooding must occur for any solution.

Finally, two rain events RK1 and RK2 (Figure 4) are used in the optimisations. RK1 represents 10 minutes storm followed by a small rain of 1 hour and whose total depth is 10.6 mm. RK2 represents a typical average rain of 4 hours duration and total depth of 20.2 mm.

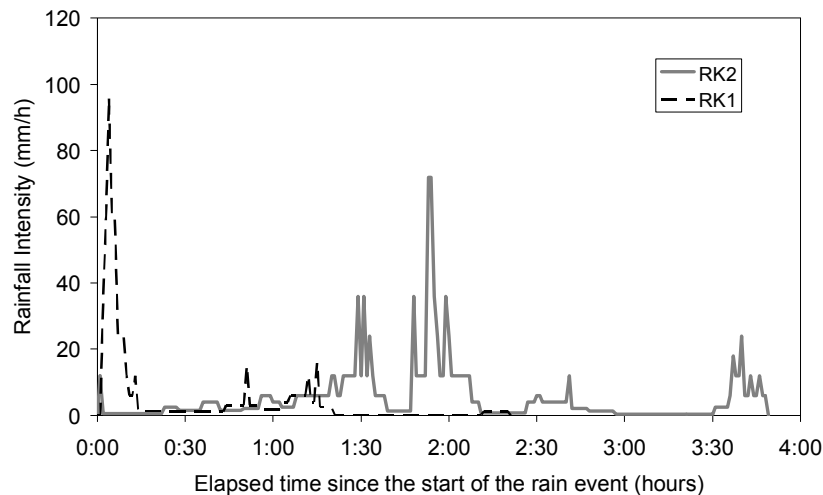


Figure 4. The two rain events considered in the case study of Kolding

2.2 Modelling tools

Modelling tools, Infoworks CS from Wallingford software (Wallingford Software, 2009) and MOUSE from the Danish Hydraulic Institute (DHI Group, 2009) have a well established worldwide reputation. They are used mainly for planning studies and operational management of sewer systems and also for advanced research studies in the fields of wastewater management and urban drainage. Both tools are capable of very detailed simulation of complex sewer systems taking into account control components and devices such as pumping/lift stations, weirs, gates, valves. Local as well as global real time control can be implemented within the models and tested to define best control strategies. These modelling tools are used commonly through comprehensive graphical user interfaces to build models, setup and run simulations. Automated optimisation, independently from the optimisation approach, requires a large number of simulation runs and thus interfacing the modelling tools with the optimisation algorithm is necessary. Infoworks CS can be interfaced with other applications through its relatively complex and comprehensive but not supported Application Programming Interface (API). For MOUSE, simulations can be configured through simple text files that are completely documented and these simulations can then be executed in batch shells.

2.3 Optimisation algorithm

The multi-objective genetic algorithm NSGA-II developed by Deb *et al.* (2000) is used in this study. This optimisation algorithm has two main features: i) it is a genetic algorithm and ii) it is a multi-objective algorithm. This approach detailed below has already been successfully applied for the optimisation of wastewater treatment plant control strategies (Beraud *et al.*, 2009).

2.3.1 A genetic algorithm

The choice of using a genetic algorithm is based on the observation that mainly two categories of algorithms are used for optimisations of nonlinear systems like the control strategy of sewer networks: techniques based on the theory of Non-Linear Programming (NLP) (Fikar *et al.*, 2005, Chachuat *et al.*, 2005) and techniques based on the theory of Genetic Algorithms (GA)

(Doby *et al.*, 2002, Holenda *et al.*, 2007, Beraud *et al.*, 2009).

A genetic algorithm (GA) has been chosen for this study. A GA is an optimisation algorithm based on cyclic evolution and evaluation of a set of potential solutions (named the population or generation), until the best solution is reached. In order to make this population evolve toward the best solution, three main operations are used, inspired by Darwin's evolution theory: the selection, the recombination and the mutation. At each cycle, these operations are performed to generate a new population of solutions (or individuals) based on the current one. First, best solutions are randomly selected. Then, these solutions are randomly recombined to generate new candidates that might evolve toward the optimum. These new candidates are finally randomly mutated to avoid to be trapped in a local best solution. At the end of each cycle, the objectives values of these new candidates are evaluated and the previous operations are repeated until the best solution is reached. More information on the detailed operation of a GA can for instance be found in Reeves (2003).

GAs have the drawback to require a large number of objectives evaluations but their big advantage is that they do not require the computation of the objectives derivatives and they are capable to find the global best solution within the search space induced by operational constraints (pumping capacities ...). GAs have hence a big advantage for the optimisation of sewer network control strategy: they can directly use simulations of a model (or even interconnected models) for the objective functions evaluations. Thus, these simulations can be based on commercial packages without any need to have access to models equations.

2.3.2 A multi-objective approach

Traditional optimisation approaches can only handle one single objective. However, many opposed objectives are typically encountered in the optimisation of sewer network control strategy: minimisation of the flooding, minimisation of the volume of CSOs, minimisation of the pumping energy... One way to handle all these objectives consists in aggregating all of them in a single one with a weighting scheme as in Eq. 2 (obj_i are the various objectives, α_i are weights and obj is the aggregated objective value).

$$obj = \alpha_1 \cdot obj_1 + \alpha_2 \cdot obj_2 + \alpha_3 \cdot obj_3 + \dots \quad (2)$$

This technique could be convenient as it is the only way to use traditional algorithms. However, the choice of the weights α_i is subjective to the knowledge of the analyst and has influence on the final solution obtained when objectives are opposite. The decision maker which will be provided with the solution is usually not involved in this choice and a frequent question is the sensitivity of the solution to a slightly different weighting scheme (Savic, 2002).

Another approach consists in adapting existing optimisation algorithms to search for what is called the Pareto front which is the set of best compromises between all opposite objectives. Best compromises are solutions for which there is no other solution which have better values for all objectives (Deb *et al.*, 2000). An illustration is provided in Figure 5 where candidate solutions are in light and dark grey and the Pareto front is in dark grey.

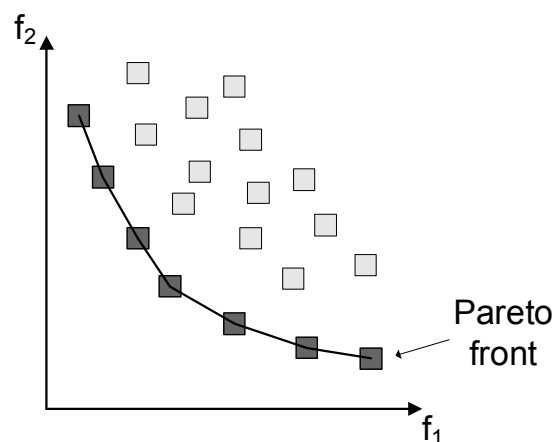


Figure 5. Example of a set of potential solutions (light and dark grey) and the associated Pareto front (dark grey)

The global solution can then be chosen inside this set of best solutions, having a clear insight into the

trade-offs involved. The big advantage of this technique is that no *a priori* weighting of the objectives is made. Furthermore, the sewer system manager has more information to make a clear choice of operating condition.

2.3.3 NSGA-II

As previously mentioned, NSGA-II is a multi-objective genetic algorithm (MOGA) developed by Deb *et al.* (2000). It is hence a genetic algorithm, capable of coupling with sewer network simulation engines to find the global best solution to the problem. Moreover, the algorithm itself has been adapted for multi-objectives problems in order to search for the Pareto front in an efficient way.

Many other alternative MOGAs are available. The two other most common ones that are widely accepted and used with a wide range of problems are the Pareto Envelope-based Selection Algorithm II (Corne *et al.*, 2001) and the Strength Pareto Evolutionary Algorithm 2 (Zitzler *et al.*, 2002). However the difference between these algorithms is tight and like it is proved in the no-free lunch theorems (Wolpert and Macready, 1997, Woodward and Neil, 2003), we believe that there is not a best algorithm for all kind of problems like our but only good adaptations and usage for each of them.

The NSGA-II is hence chosen since it has already been successfully applied in many applications, like for instance the optimisation of WWTP control strategies (Beraud *et al.*, 2007), of the sewer network design (Guo *et al.*, 2006) and of the control of integrated wastewater systems (Fu *et al.*, 2008). Moreover, since the authors are familiar with this algorithm, its usage is believed to more easily give good results.

2.4 Coupling approach

In order to perform the optimisation of the sewer network control strategy, two pieces of codes have to be coupled: the genetic algorithm and the simulation engine. A third piece of code is even necessary to process the output of the simulation engine in order to compute optimisation objectives. These three components have to be linked together.

In this study, the original simulation engine is used (namely Infoworks CS and Mouse). As previously stated, this allows having precise results as well as a good potential of methodology dissemination. On the other hand, the NSGA-II is available either as a standalone C code or as MATLAB functions. Since post-processing of simulation results is required, the MATLAB solution seemed to be more practical. NSGA-II and the performance calculations are hence coded with MATLAB while the simulation engine stayed the same, as shown in Figure 6. For each potential solution of NSGA-II, MATLAB modifies the parameters of the simulation, either via the API for Infoworks CS or via the input text file for Mouse (UND file). MATLAB then launches the simulation. Once the simulation is completed, results are exported from the simulation engine into a text file and then imported from this text file into MATLAB which finally computes the objective values out of these imported datasets.

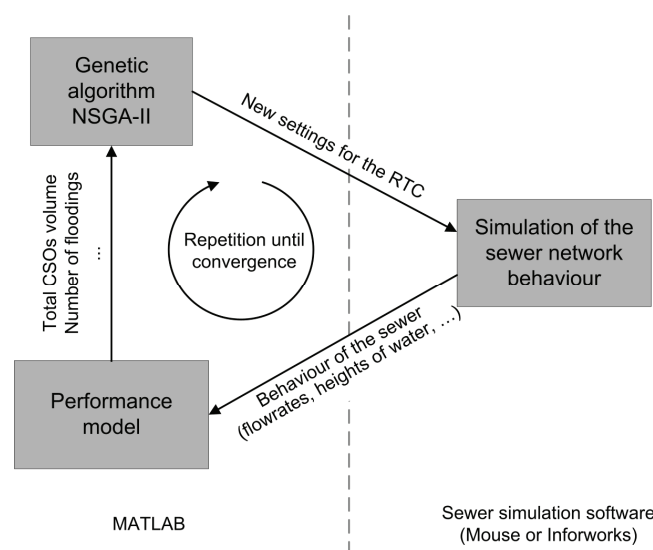


Figure 6. Coupling of NSGA-II with existing sewer simulation software

3 RESULTS AND DISCUSSION

3.1 Berlin case study

The results of the Berlin case study are presented in Figure 7. The initial performances are also presented for comparison. For each rain event, 40 generations of 200 individuals each (8000 simulations) were performed with a random starting generation. One observes a difference in the shape of the Pareto front between the two rain events. The interpretation of this difference is not obvious; however it might be related to the difference in the dynamics of the two rain events. By comparing the initial performance to the Pareto front, it is obvious that the initial configuration of the control strategy was set to reduce the volume of CSO at the storage tank since no significant improvement has been found for both rain events. The same comparison shows that, for the same minimal CSO volume at the storage tank, the total volume of the upstream CSOs can be reduced by 292 m³ (-34 %) for RB1 and by 455 m³ (-12 %) for RB2.

The Pareto front shows also that upstream CSOs can be reduced to zero but as consequences the CSO volume at the storage tank will increase by 5000 m³ (+45 %) for RB1 and by 7000 m³ (+30 %) for RB2. Considering the total volume of CSOs, the later option is a bad trade-off between upstream CSOs and de the CSO at the storage tank.

The trade-off between these two objectives might have more sense when considering the settling potential of the storage tank. According to BWB, the storage tank has a suspended solids retention efficiency of 50 %. Subsequently, if the extra volume of CSO at the storage tank is less than two times the upstream CSOs volume reduction, then less suspended solids/pollutants are discharged to the receiving water. After examining the Pareto fronts of both rain events, it was found that this trade-off was not advantageous.

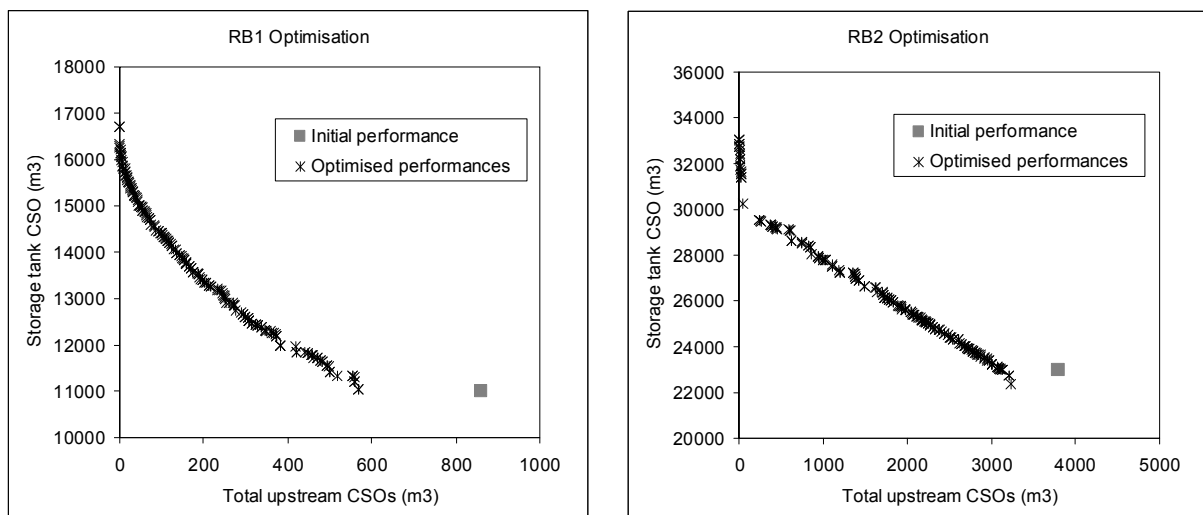


Figure 7. Results of the control optimisation for the two considered rain events

3.2 Kolding case study

The results of Kolding control strategy optimisation and initial performances are presented in Figure 8. For each rain event, 100 generations of 100 individuals each (10000 simulations) were performed with a random starting generation. For the RK2, only very small improvements are possible. The optimisation has found a solution that reduces the volume of CSO from 12432 to 12403 m³ (-29 m³ or -0.25%) for almost the same energy. This is really negligible but still important information indicating that this rain event couldn't be better handled. This finding is quite normal since the considered storm event is very difficult to handle.

For RK1, the first remark is that the current performances are once more very close to the Pareto front. However, a solution involving more energy (7515 kWh instead of 7470 kWh, +0.6%) is capable to reduce the volume of CSO by 350 m³ (38103 m³ instead of 38456 m³, -1%). On this rain event, the control strategy could hence have a better performance if it is adequately optimised. The form of the Pareto front finally indicates that there is a linear dependency between the energy transferred to the water and the total volume of CSOs.

If this is quite intuitive, the slope of this dependency (here +1kWh of energy for -8.5m^3 of CSO) can be of great help to indicate whether it is more profitable to reduce the volume of CSOs or to let some CSOs occur because it will cost too much energy to further reduce them.

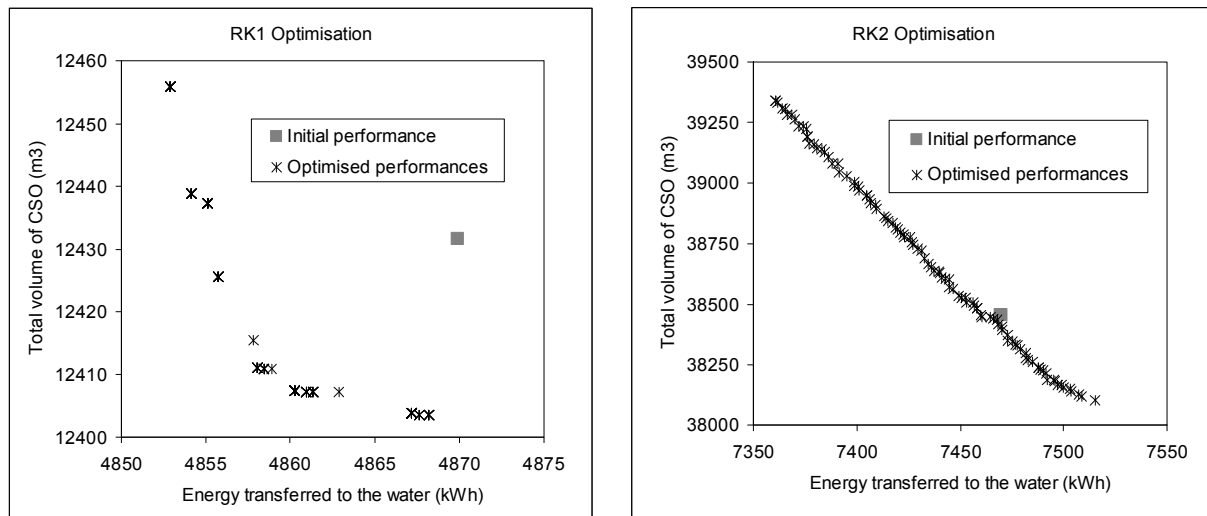


Figure 8. Results of Kolding control strategy optimisation for the storm event (left) and rain event (right)

4 CONCLUSIONS

This paper discusses the use of advanced optimisation algorithms along with sewer networks modelling tools to optimise control settings. The first optimisation runs on both case studies showed promising results. The method provided in each case control settings fulfilling contradictory objectives. The coupling of NSGA-II multiobjective genetic algorithm with state of the art sewer simulation software allows a rapid application of the optimisation technique. The case studies presented are a good demonstration of the application potential and it is very likely that greater improvements would be found with further optimisations. The Pareto fronts found at the end of the optimisation runs, allow making balanced decisions between multiple objectives depending on circumstances and on sewer system managers priorities. Practical implementation of the approach and implementation of optimal solutions found still has to be performed and this will be addressed in further work.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of the Berliner Wasserbetriebe, the city of Kolding and Krüger (Veolia Water Solutions & Technologies - Denmark) by providing data, models and technical help.

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