REAL-TIME FLOOD CONTROL BY MEANS OF AN IMPROVED MPC-GA ALGORITHM AND A FAST CONCEPTUAL RIVER MODEL FOR THE DEMER BASIN IN BELGIUM

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ABSTRACT: An important flood control strategy is to install large retention reservoirs in which excessive water can be stored during periods of extreme rainfall. Adjustable weirs regulate these reservoirs. To use the storage capacity of the reservoirs most efficiently, the weirs should be controlled in an optimal way. For that purpose, the technique of MPC-GA has been implemented to minimize the total damage cost in the basin. It generates several future scenarios of gate positions and selects the best scenario, based on simulation results with a conceptual river model. To improve the efficiency of the optimization, a more goal-oriented MPC-GA technique has been developed. This involves grouping of the weirs at different levels and phasing of the optimization process.

Key Words: Real-time flood control, model predictive control, genetic algorithm, conceptual model

1. INTRODUCTION

Storms and floods are the natural disasters that cause the highest amount of economic damage. The frequency of extreme rainfall events has been increasing during the last decades and will further continue to increase in the 21st century. Together with the urbanization trends, temporal climate variations and trends may cause increased surface runoff, river peak flows and related flood frequencies; as was shown for many places of the world, also Belgium (Poelmans *et al.*, 2011; Ntegeka *et al.*, 2014). Since floods are often accompanied with huge environmental, economic and human damage, there is a need for adaptation actions.

Retention reservoirs are often installed to limit floods by temporarily storing water. The reservoirs can be filled during periods of high rainfall and emptied during dry periods. The inflow and outflow of water in the reservoir is regulated by means of adjustable weirs. The difficulty is to determine at what time moments the reservoirs should be filled and emptied and with which amounts.

To make use of the reservoir storage capacity in the most optimal way, the regulation of the weirs needs to be optimized. Malaterre *et al.* (1998) has listed different techniques that were investigated to control river systems. However, not every control technique is applicable for the purpose of flood control. For example, PI and heuristic controllers (Litrico *et al*., 2006) cannot handle the typical non-linear behavior of the river system during floods. Model Predictive Control (MPC), a technique whereby a river model is used to predict future states of the system, has already been applied successfully for set-point control of river reaches (Rutz *et al.*, 1998), to control irrigation canals or open water systems (Schuurmans *et al.*, 1997; van Overloop, 2006; van Overloop *et al.*, 2010; Negenborn *et al.*, 2009) and for flood control (Barjas-Blanco *et al*., 2010). In Van den Zegel *et al.* (2014) the MPC-technique is combined with a genetic algorithm (GA) and applied for the purpose of flood control. The research presented in this paper is a follow-up of that work and investigates how the MPC-GA technique can be further improved.

Section 2 first provides an overview of the study area of this research, the Demer basin in Belgium. Section 3 thereafter explains the MPC-GA technique, followed by a presentation of the results in Section 4 and a discussion on improvement of the technique. The paper ends with the main conclusions and recommendations for future work in Section 5.

2. STUDY AREA: DEMER BASIN (BELGIUM)

The Demer basin, one of the eleven river basins in Flanders (Belgium), had to deal with large floods several times during the past years (e.g. September 1998, January 2002, November 2010). As part of the flood management strategy, hydraulic regulation structures and large retention reservoirs were installed by the Flemish Environment Agency (VMM). Despite the fact that these measures strongly reduced the flood frequency in the basin, floods still occur. Therefore, the Demer basin is a very interesting study area to investigate possible improvements of flood control techniques.

2.1 Current control strategy

In the current control strategy, the weirs are regulated according to a set of rules, which are fixed based on experience. These rules typically have an if-then-else structure and are mostly based on the up- and downstream water levels of the weirs. Due to this local control, the interaction of the different weir regulations is not taken into account. The regulations also cannot anticipate on near-future rainfall predictions. Because of the complexity of the river system, it is expected that the regulation with such expert-based fixed rules is suboptimal. A better way is to make use of a river model that can deal with these interactions and predict future states of the system as part of a more intelligent control strategy.

2.2 Conceptual model

As a component of their flood forecasting system (www.waterinfo.be), VMM has implemented a full hydrodynamic model of the Demer basin in Infoworks^{TM}-RS. In this detailed model the Saint-Venant equations are solved explicitly, which leads to an excessive calculation time for real-time control. To overcome this problem, Meert (2012) has calibrated a much faster and simpler conceptual model to this detailed model. The developed model operates in the Simulink$^{®}$ environment and contains the two largest flood control reservoirs of the Demer basin, called Schulensmeer and Webbekom, and their compartments. This conceptual model is used in this research on the basis of the MPC-GA technique. Both the full hydrodynamic model and conceptual model use catchment rainfall-runoff as input, obtained from the conceptual rainfall-runoff model PDM, as implemented in Infoworks^{TM}-RS. Historical rainfall events are used as input. So far in this study, the uncertainty in the rainfall predictions is not taken into account.

3. METHODS

The MPC-GA technique is a combination of the Model Predictive Control technique (MPC) and a Genetic Algorithm (GA), as explained in the next sections.

3.1 Model Predictive Control

Model Predictive Control is a popular method for solving optimization problems. The algorithm aims to minimize an objective function by optimizing the control variables (weir crest levels in this case) in the system. Thereby it makes use of a model that can simulate future states of the system. In real-time control, during every optimization step an optimization over the prediction horizon takes place. The obtained optimal values for the control variables during the first time step are then applied to the actual system during the next optimization step. Due to uncertainties (model uncertainty, uncertain rainfall predictions, …) the state of the model may differ from the real system state. Therefore, model updating based on data assimilation is applied for each optimization step in order to minimize these differences.

In this study, the main objective is to minimize the total flood damage in the river basin. This flood damage is computed along twenty flood-prone locations as a function of the inundation depth.

3.2 Principle of MPC-GA

The MPC-GA algorithm consists of several components. The first component is a genetic algorithm that generates different time series of gate levels for the prediction horizon (48h in this study) for each adjustable weir in a semi-random way. Secondly, these series of gate levels are applied to the river model, together with catchment rainfall-runoff simulation results. The water levels computed by the river model at the desired locations are obtained and transferred into damage cost by means of the damage functions. This process of generating series of gate levels, applying them to the river model and calculating the total damage is repeated several times during each optimization. Finally, the total damage cost corresponding to each of these cases is determined and the case (series with gate levels) with the lowest total damage cost over the prediction horizon is selected for application at the next optimization step.

Because a large amount of model simulations are required in the optimization process, full hydrodynamic models cannot be used; their calculation times are too long. The faster conceptual model is used instead. The application of river conceptual models has been investigated by Wolfs et al. (2013), Meert et al. (2012) and Chiang et al. (2010) and were considered appropriate for the purpose of flood control.

3.3 Genetic algorithm

Chiang *et al.* (2014) describes the functionality of a Genetic Algorithm. The main principle is that in every time step, a new gate position is found as the sum of the previous position of the gate and a semi-random deviation. Van den Zegel *et al.* (2014) has adapted this technique such that smooth gate level series are obtained over the prediction horizon; hence to avoid unstable series with strong temporal fluctuations. In this way, realistic and desirable series are obtained.

The random nature of the GA based optimization has both advantages and disadvantages. On the one hand, because of the inherent randomness involved, a lot of calculations need to be executed to obtain an acceptable solution, which makes the process time consuming. On the other hand, the solutions will always evolve towards the global optimum and have no risk to get stuck in a local optimum. For scientific research and larger study areas with more adjustable weirs, it is preferable to develop a more goal-oriented algorithm that converges faster. This research investigates if this is feasible by dividing the total set of adjustable weirs into groups and phasing the optimization.

3.4 Improved MPC-GA: Grouping weirs and phasing the optimization

The technique of grouping the adjustable weirs is based on the assumption that the regulation of some of the weirs only has a minor impact on the regulation of other ones. In such cases, the weirs can be divided into groups which are optimized separately. In that way, the complexity of the optimization process is strongly decreased. Hereafter, an example is provided on how these groups can be formed and help to speed up the optimization process. In Figure 1, the adjustable weirs are represented by hollow rectangles. The basin is divided into two main groups being Schulensmeer (group 1; 5 weirs) and Webbekom (group 2; 7 weirs). Both groups can be divided further into respectively two (1.1 – 1.2) and three (2.1 – 2.2 – 2.3) subgroups, as illustrated in Figure 1.

Let us consider the example shown in Figure 1 and Table 1. It is based on three phases in the optimization process. Note that the total amount of phases may strongly differ in other cases, and depends on the number of weirs considered per group. To guarantee good results, it is recommended to transfer some of the best cases of the previous optimization step to the current one. This happens in phase 1. In phase 2, optimization at the level of the two main groups is executed. In the first part of this phase, called subphase 2.1, the regulation of the weirs near Schulensmeer is optimized while the regulation of the weirs near Webbekom is considered unchanged and taken equal to the series of the best case so far. In the subphase 2.2, the weirs near Webbekom are optimized. In phase 3, this process is repeated for the other (secondary) groups of weirs. By doing so, the best case is fine-tuned in a more efficient way. It is nevertheless important to start at the higher level to decrease the probability of converging to a local optimum instead of the global optimum. It moreover has been shown that it would be more efficient to iterate each phase with a smaller number of cases in each subphase, than to execute each phase only once but with a larger number of cases in each subphase. In the example shown here, 200 cases are considered in total and phase 3 is repeated two times.

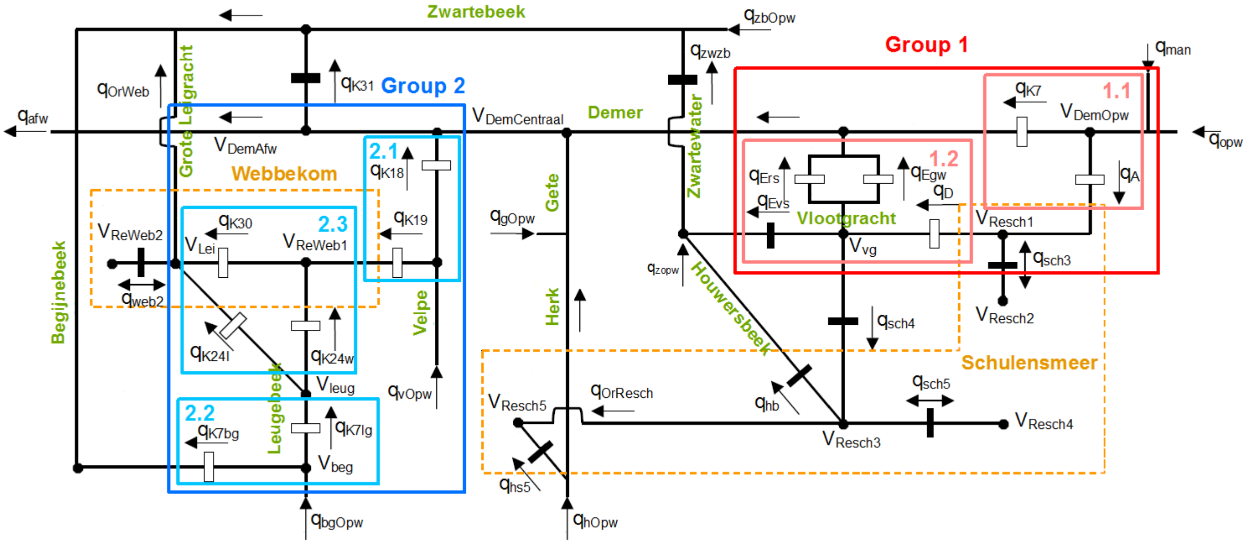

Figure 1: Division of the set of adjustable weirs along the study area into groups and subgroups

Table 1: Example of grouping weirs and phasing the optimization

Phase	Number of iterations	Input	Optimized group	Number of optimized weirs	Number of considered cases	Output
1	1	4 best cases of previous optimization	/	0	4	4 best cases
2	1	Best case from previous phase	1	5	32	4 best cases until now
		Best case from previous subphase	2	7	64	4 best cases until now
3	2	Best case from previous phase	1.1	2	10	Best case from subphase
		Best case from previous subphase	1.2	3	10	Best case from subphase
		Best case from previous subphase	2.1	2	10	Best case from subphase
		Best case from previous subphase	2.2	2	10	Best case from subphase
		Best case from previous subphase	2.3	3	10	4 best cases until now

4. RESULTS

4.1 Results of the original MPC-GA algorithm

The efficiency of the MPC-GA algorithm is investigated for the case study of the river Demer in Belgium, whereby the results obtained with MPC-GA are compared to those obtained with the current regulation strategy of VMM by means of fixed rules. Table 2 compares the highest exceedance of the flood level and the flood duration for twenty flood-prone locations during the historical event of September 1998. Figure 2 shows the flood volume over time.

Table 2: Highest exceedance of the flood level and the flood duration for twenty flood-prone locations for the historical flood event of September 1998, after application of MPC-GA and the current regulation strategy based on fixed rules

Locations	Highest exceedance of flood level [m]		Flood duration [h]	
	Fixed rules	MPC-GA	Fixed rules	MPC-GA
DemOpw	-	-	-	-
Velpe	-	-	-	-
BegOpw	-	-	-	-
HerkOpw	-	-	-	-
Resch1	0.03	-	10.50	-
Resch2	0.03	-	10.33	-
Resch3	-	-	-	-
Resch4	-	-	-	-
ReWeb1	-	-	-	-
K7afw	-	-	-	-
MondGete	0.25	0.14	48.50	33.92
MondVl	0.07	-	19.83	-
K31Opw	-	-	-	-
ZwaOpw	0.51	0.48	89.25	88.83
Vlootgr	0.60	0.28	69.58	41.75
K31Afw	-	-	-	-
Begijnenb	0.05	-	15.67	-
Leugeb	-	-	-	-
Leigracht	0.13	-	34.92	-
DemAfw	0.33	0.29	74.58	74.58

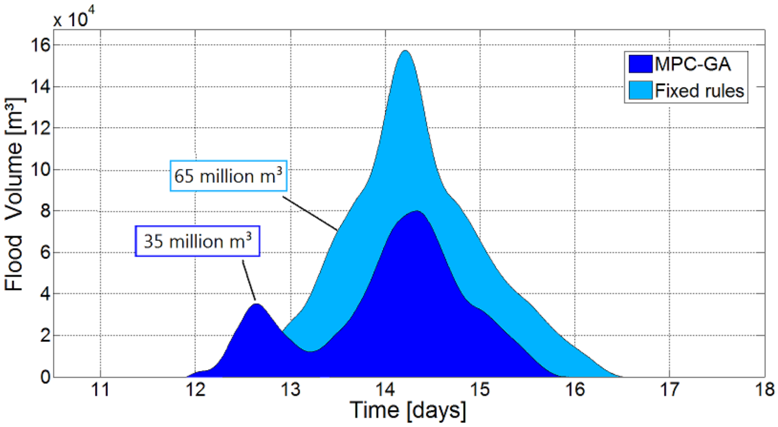

Figure 2: Comparison of the time series of total flood volume along twenty flood-prone locations for the historical flood event of September 1998, after application of MPC-GA and the current regulation strategy based on fixed rules

It is clear from these results that the MPC-GA algorithm is capable of reducing the highest exceedance of the flood level significantly. It also succeeds to reduce the flood duration. The total flood volume for the September 1998 event is reduced by 46%. Also for other historical events similar improvements are obtained (not shown).

Figure 3 provides an overview of the total damage cost obtained after different simulations of the MPC-GA algorithm, and how the cost depends on the number of cases that are considered during each optimization step. It is clear that the mean total damage cost and the variation in damage cost decrease when the number of cases considered increase. This is a logical outcome: if more cases are simulated, the chance of the MPC-GA-algoritm to find a solution close to the global optimum increases. Despite the fact that already major improvements are achieved with only a limited number of cases considered, it is interesting to investigate how the mean and the variation in total damage cost can be reduced when only limited computer capacity and calculation time would be available.

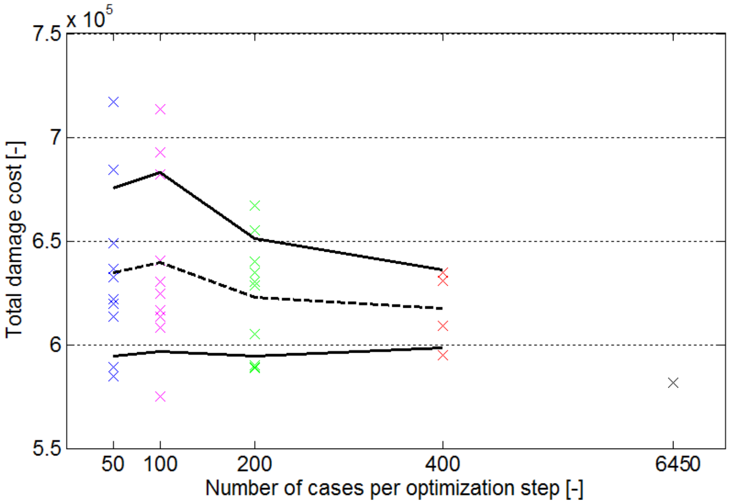

Figure 3: Total damage cost along twenty flood-prone locations for the historical flood event of September 1998, after application of MPC-GA, in function of the number of cases per optimization step

4.2 Results of the improved MPC-GA algorithm

To investigate whether the improved MPC-GA algorithm actually leads to better results, an experimental study was conducted. Thereby simulations were done for three different versions of the algorithm. The first algorithm is the original MPC-GA algorithm, of which the results are shown in the previous section. The second one is the improved algorithm as discussed in section 3.4, based on the example shown in Table 1. The third algorithm only consists of phases 1 and 3 of the improved algorithm. The total number of considered cases in each algorithm was 200 (equal total calculation time) and the time step between two optimizations was set to six hours. Figure 4 shows the results obtained with these different models. The dotted line indicates the mean total damage and the other lines show the variation in the results. When comparing the improved algorithm to the original MPC-GA algorithm, it is clear that the mean total damage as well as the variation have improved. This is caused by a more optimal use of the storage capacity in the retention reservoirs. The outlier is probably due to the small number of cases considered and the large optimization step. Results however show that the proposed method of grouping weirs is very promising and deserves further investigation.

The importance of optimizing at different levels is shown by the results of the third algorithm, the one where the second phase is eliminated and the third phase is iterated four times instead of two times. The mean total damage cost of the simulations is comparable with that of the original algorithm but the variation is much larger. This indicates that the results are more likely to be obtained by coincidence than by a goal-oriented optimization. In most of the simulations only a local minimum is obtained. However, one of the simulations has a very low total damage cost. This shows that optimizing at lower levels is important for reaching a faster convergence. The results of the second algorithm confirm this. Based on these simulations, it is found that in 85% of the optimization steps an improvement was obtained during the third phase. The average gain in damage cost in this phase was 4%. The above shows that it is discouraged to immediately optimize at the lowest level. A first optimization on the higher level is required to reach a result close to the global optimum. Afterwards the level is lowered to fine-tune the regulation step by step and to reach faster convergence of the optimization algorithm.

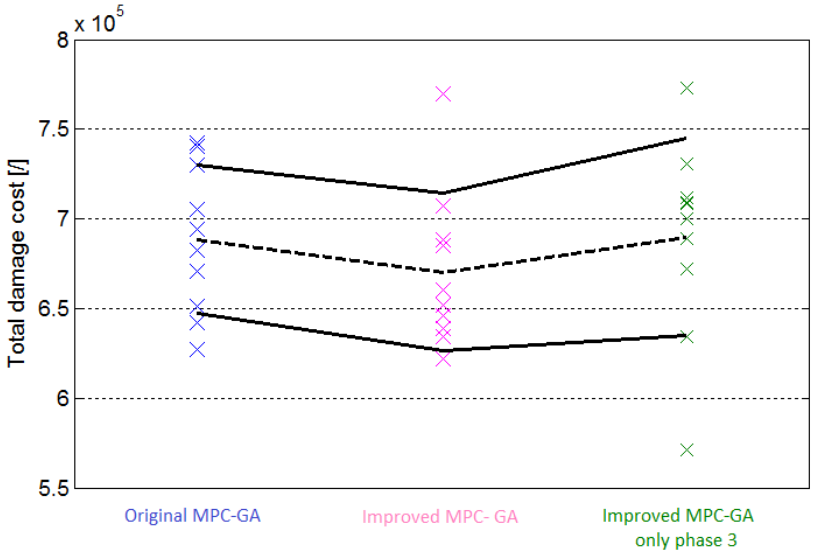

Figure 4: Comparison of the total damage cost along twenty flood-prone locations for the historical flood event of September 1998, after application of three different MPC-GA algorithms

5. CONCLUSIONS AND FUTURE WORK

This research has shown, based on the case study of the Demer basin in Belgium, that MPC-GA is a promising technique for real-time flood control. The algorithm manages to reduce the duration of floods as well as the maximum exceedance of the flood levels in comparison to the current fixed rules. For the historical event of September 1998, the total flood volume was reduced by 46%.

Although good results are already obtained, it is important to further test and improve the efficiency of the algorithm. This requires further statistical investigations by means of long-term simulations. It also would be useful to test the applicability of MPC-GA to larger river basins, and for cases with limited computational capacity. In support of such cases, this paper proposed a technique whereby the adjustable weirs of a river system are grouped at different levels and the optimization is executed in several phases. The methodology has proven to be very promising and will allow the algorithm to converge faster. This technique will be further investigated in the near future.

During this research, historical events were used for the simulations, which means that the uncertainty in the rainfall predictions was not taken into account. However, this uncertainty can be an important factor for real-time control. The influence of input and model related uncertainties on the efficiency of the algorithm needs further investigation as well.

6. ACKNOWLEDGMENTS

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