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A DSS FOR RESERVOIR OPERATION BASED ON THE EXECUTION OF FORMAL MODELS

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Controlling the evolution of a reservoir in a flood episode can be critical, especially in Mediterranean basins where the concentration time is very short. In this situation, an automatic software tool can help the reservoir manager to make quick decisions. In this paper we present a DSS based on the execution of formal models by means of model checking. This technique exhaustively explores the different execution branches of a model of the system.

The DSS addresses two flood control tasks. First, the DSS simulates the evolution of the reservoir (the water stored and released) when applying a predefined flood control strategy. Second, and probably the most important task, the DSS generates, in a short time, new flood control strategies based on a prediction of the water inflow and the goals and constraints imposed by the dam manager. This task is associated with the concept of risk in its technical sense; that is, the probability of an extreme event occurring and the damage cost associated with such an event. The DSS returns a set of maneuvers over the dam gates that control the evolution of the dam level following the goals and constrains imposed by the dam manager.

INTRODUCTION

Efficient dam management is a complex and critical task. The objectives of dam management are twofold: the efficient use of water resources and flood control. Dam management has to consider different aspects, such as the different outlets, the uncertainty regarding the real water inflow or even the temporal breakdown of some outlets. Dam operators usually estimate the input hydrogram (inflow) based on official forecasts. They employ a pre-designed catalog of decision rules which take into account different parameters (reservoir level, forecast, current downstream capacity, etc.). These rules should be adapted to unexpected situations, such as breakdowns or failures of their elements.

Some dams are especially sensitive to these situations. For instance, the case study presented in this paper has a short concentration time (around 6 hours) and a wide catchment area. These specific characteristics cause a rapid increment in the dam level leaving little time to make a decision. Additional stressful situations, caused by communication errors or failures in outlets,

may significantly complicate the decision-making process. In such a complex situation, a software tool that quickly simulates and suggests ways to manage the outlets may help operators decide safely and efficiently.
BeDam is a Decision Support System (DSS) for reservoir operation in flood episodes that has been developed by Abengoa and the University of Málaga. It combines simulation and optimization techniques, providing all the sequences of operations that satisfy the objective defined by the dam manager. The proposed operations and their effects provide more information than the traditional range of solutions presented by intuition and experience. BeDam is based on the use of model checking [4], a technique that performs the controlled execution of a given system model, described with specific languages, in order to generate the system's reachability graph. This controlled simulation is enriched with methods for searching for specific properties, very efficiently way.

This paper has been inspired by Gallardo et al. [5] where we proposed using modeling languages with non-deterministic features and the search capabilities of model checking to synthesize controllers for dam management. We implemented this approach using the model checker SPIN [7], which has been previously used in real water related applications, including the verification of the flood control barrier in Rotterdam [9]. Our method consists in approximating, from a non-deterministic controller, an acceptable deterministic controller through transformations. In our case, the transformation consists of removing the non-determinism. Here, we present novel results in several aspects. On the one hand, the mathematical models of the dam include different types of outlets, and it is possible to manage a larger number of elements and opening degrees. On the other hand, it is possible to analyze longer flood episodes. In addition, BeDam includes a simulation module, which shows the effects of applying different discharge policies. We have also developed a graphical user interface that integrates all the elements (models, simulation, and optimization module) in a single tool, facilitating the configuration of the models for simulation, the specification of optimization objectives and the visualization of results. Finally, the whole system has been calibrated to improve the tool's precision.

The paper is organized as follows. First, we compare BeDam with other existing DSS for reservoir management optimization. Then, we introduce the main features of BeDam. The fourth section presents a case study, La Concepción dam. Finally, we present some conclusions and future work.

RELATED WORK

In order to minimize the social impact on human livelihoods produced by flood control operations over the last few decades, and thanks to a rise in the use of computational analysis techniques for dam management, governments have stimulated programs where DSSs play a fundamental role [10]. This effort has produced systems like SAD-Ebro in Spain [11,12], IMSFCR in China [2], FC-ROS in Poland [8] and DESMOF in Canada [1]. These DSSs cover all phases of the flood management process, from data acquisition and flood forecasting, to the control of reservoirs.

For instance, IMSFCR (Integrated Management System for Flood Control of Reservoirs) has a specific module that generates operating alternatives which are composed of a series of constant or gate regulated releases. Then, the alternatives are evaluated with the fuzzy iteration method of reservoir flood operation. FC-ROS (Flood Control-Reservoirs Operator's System) lets the operator choose several pre-designed control policies instead of automatically generating operations. DESMOF (Decision Support for Management of Floods) includes a module for simulating the operation of flood control structures, using IF-THEN-ELSE statements to define the operating rules. To reduce the number of simulations, they integrate human expertise and heuristic knowledge in an expert system. In addition, computational models have been used to manage other structures for water storage, different to dams, like in Gaur et al [6] where artificial neural networks are used to find the optimal location of wells for the management of groundwater of the Dore River in France, the idea being to minimize the pumping cost of the wells. Cheng and Chau [3] propose a model that provides decision support for pre-release operation of a single-reservoir in flood episodes caused by typhoons. This DSS only estimates the risk of a water supply shortage derived from an alternative pre-release decision. The experiments presented show that pre-release reduces the flood without significantly increasing the risk of a shortage.

In Spain, there are other DSSs for flood control, such as [11-13]. This system integrates several mathematical models that estimate the time evolution of levels and flows along the different watershed rivers. Among these models, there is one in charge of describing and calculating the discharge evolution along the rivers in the basin. This DSS can simulate the effects of applying different discharge strategies in the river basin's dams, for instance the Dordogne strategy.

In most cases, flood control is based on predefined operating rules that return the discharged water in a time period. BeDam supports the simulation of predefined operating rules. The main difference between BeDam and the aforementioned DSSs is that the optimization carried out by BeDam also provides the actual maneuvers that must be carried out. In addition, it can also optimize the reservoir operation by producing pre-release maneuvers, as in [3, 13]. The optimization of a reservoir's management is a difficult problem that can be addressed with several techniques [1-4, 9]. The main problem is how to deal with the hybrid behavior of dams; that is, it is necessary to consider not only continuous equations that determine the discharge capacity, but also the control modes of the outlets, which are discrete elements. BeDam is based on the exhaustive exploration of the models' execution [4]. It uses a hybrid model of the dam; with continuous variables, such the volume, the level and the outflow of each outlet, and discrete variables, such as the state of the outlets. In addition, BeDam includes a dam operator model that non-deterministically changes the state of the outlets in concrete time instants. This model decides which maneuvers to apply from among the set of possible actions. Compared with the optimization methods commonly used in dam management [10,13], BeDam's models provide an accurate behavior of the dam without having to solve complex dynamic systems, and the optimization algorithm analyzes whether or not specified constraints regarding inflow and initial reservoir volume are feasible.

THE BEDAM APPROACH

BeDam is a DSS based on executable models and algorithms for simulation and optimization. BeDam provides two operating modes. On the one hand, given an inflow prediction, the tool simulates the behavior of the dam when applying a specific discharge policy. On the other hand, BeDam also supports the optimization of the discharge policies and the generation of maneuvers. Thus, for a given objective such as maintaining the dam level under some value, the tool returns how the dam manager should operate the outlets to achieve this objective. In this section we present the different elements of BeDam architecture, depicted in Figure 1.

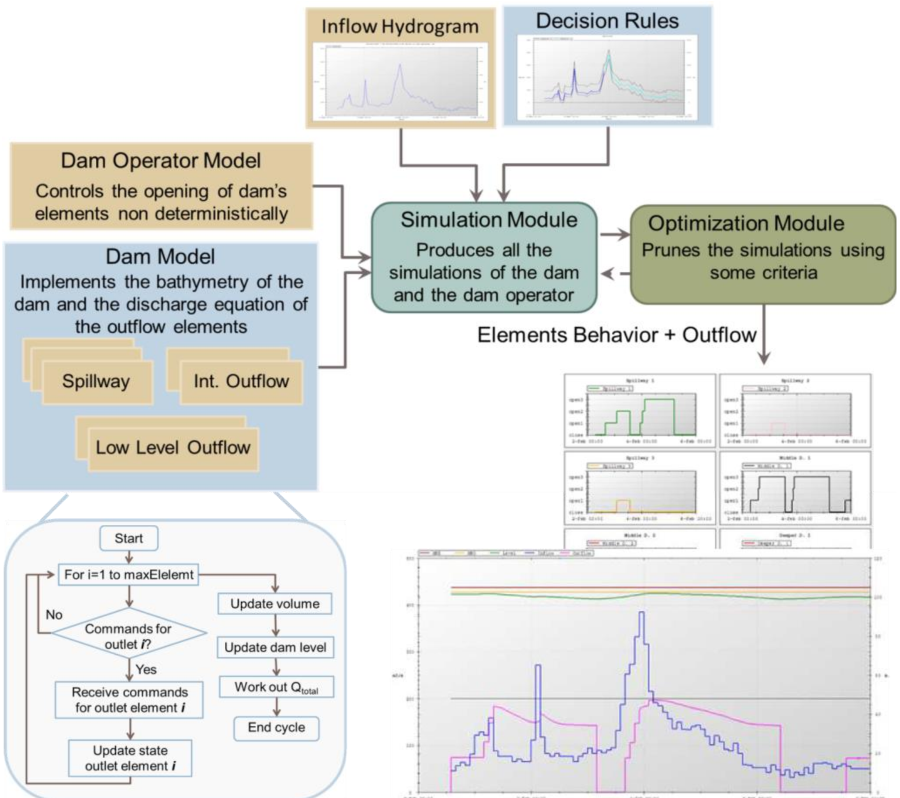

Figure 1 BeDam Architecture

Dam model

The behavior of the dam is defined by a set of equations that specify the discharge curves of the different outlets, the dam level and the stored volume. These variables evolve continuously over time, but also depend on other continuous or discrete variables, such as the opening degree of the outlets. For instance, Equation 1 describes one spillway discharge curve (outflow capacity) when it is in free discharge (completely open), where Q(t) is the discharge capacity, C_0 is the weir coefficient that is modulated by α depending on water height, L is the useful width, and h(t) is the water height.

$$Q(t) = \alpha \cdot C_0 \cdot L \cdot h(t)^{3/2} \tag{1}$$

$$Q(t) = \frac{2}{3} \cdot L \cdot K \cdot \sqrt{2 \cdot g}\,\left(\sqrt{h_1(t)^3} - \sqrt{h_2(t)^3}\right) \tag{2}$$

$$\frac{dV(t)}{dt} = Inflow(t) - Outflow(t) \tag{3}$$

Equation 2 specifies the discharge capacity when the spillway is partially open, h1- h2 being the aperture and K a coefficient that depends on the aperture. Similarly, we can describe the discharge capacity of other types of outlets. Finally, Equation 3 describes the variation of volume in the dam, which is the difference between the water inflow and the sum of water discharged by each outlet.

This modeling strategy is based on modules that specify the behavior of the different outlets, instead of a complex compact model of the dam. This approach allows us to easily implement BeDam in other reservoirs by means of new modules that specify the discharge curves of new outlets, and adapting the dam operator model to the configuration of the new dam. The basic actions performed by the dam model are depicted in Figure 1. First, it checks whether or not the dam operator has sent a command to modify the configuration of some outlets; accordingly, it changes the state of the outlets, updating the discharge equations and working out the corresponding coefficients; and finally, it works out the dam's total discharge capacity, volume and level at the current time instant.

Dam operator model

Each operating mode of the DSS (simulation and optimization) uses a different type of operator model. On the one hand, the simulation mode uses a deterministic dam operator (DDO) model; that is, for a given episode the DDO model always carries out the same maneuvers. We have used different DDOs to model traditional discharge policies. On the other hand, the optimization mode uses a non-deterministic dam operator (NDDO) model, i.e. the DDO model may carry out different maneuvers for a concrete episode.
Figure 2 shows a simplified diagram of a NDDO. Its simulation produces several management strategies. In this case, decisions are principally based on the state of the outlets and on the dam level. The non-deterministic blocks compress the different alternatives, which can be resumed, such as opening the outlets by any given degree, or doing nothing during this period. We use the optimization module to select the maneuvers of the NDDO model that meet some given criteria. To ensure the management of the dam is as close as possible to reality, the dam operator model periodically accesses the dam state, and can only act over the outlets in these time instants. In this way, we also improve the performance of the tool. Currently this period is adaptable to each dam's situation.

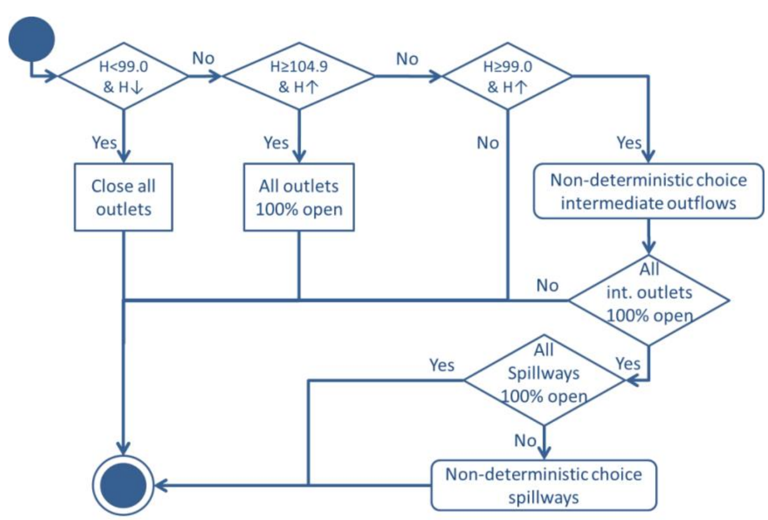

Figure 2 NDDO decision diagram

Simulation and optimization modules

BeDam's main components are the simulation and the optimization modules (see Figure 1), which are based on model checking. A basic model checking algorithm performs an exhaustive search of all the system's possible execution paths (reachability graph), checking whether the user defined objectives are satisfied or not.

The simulation module executes the models to provide the evolution of some variables over time, such as the dam level or the outflow. This corresponds to generating the system's reachability graph. If the dam operator model is deterministic, there is a single execution path. However, if an NDDO is used, the reachability graph has multiple paths, as shown in Figure 3 (a). At each decision instant, different actions may be carried out non-deterministically, which may produce several execution branches.

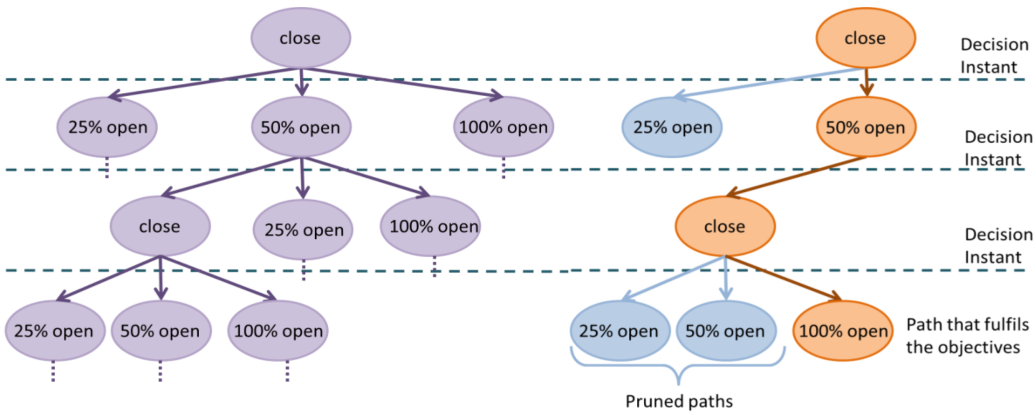

Figure 3 (a) Simulation tree (b) Pruned simulation tree

The optimization module searches execution paths that meet certain criteria imposed by the user, such as the maximum/minimum dam level required, the total outflow expected, etc. To this end, the simulation module executes the NDDO model and at the same time the optimization module prunes the generation of the different execution paths according to the defined objectives. Figure 3 (b) shows how the optimization module stops the execution of a path when this does not fulfill the criteria and forces the backtracking to a previous decision instant to execute a different path.

The standard use of the whole tool is as follows. First, the user selects the input hydrogram and specifies the duration of the episode. With this information, BeDam simulates different discharge policies. The user can examine the evolution of the dam for each policy. The second step is to specify the desired dam evolution by means of objectives and to determine the set of operations that satisfy them. The objectives may be defined using the results of previous simulations or by imposing constraints. Then, the optimization module selects one of the NDDO's execution paths that lead to a similar behavior of the dam. The result of executing this second analysis is the evolution of the dam level, the outflow and state of the outlets.

CASE STUDY: LA CONCEPCION DAM

La Concepción is a medium sized gravity dam located on the Mediterranean coast of Spain. It has a short concentration time (6 hours), and supplies a population of approximately 1,200,000 people in the summer. Its location and other characteristics, makes its management a critical task. For instance, the mean yearly inflow is higher than the capacity of the reservoir. The dam has three spillways at 99.50 m, two intermediate outlets at 66.75 m, and two bottom outlets at 46.50 m. The dam model assumes that each outlet has three possible opening degrees, which correspond to 25%, 50% and 100% open. When the reservoir level is at its maximum and all the outlets are 100% the dam's discharge capacity rise to 765 m^3/s.

We have used a historic flood episode that took place in 1989 to calibrate the dam operator models. This episode showed the peak historical flood with 520 m^3/s. Initially the level of the dam was 101.24 m and all the outlets were close. We define two management objectives. The first is to produce a peak outflow lower than 200 m^3/s, to avoid flooding urban areas. The second is to maintain the dam level below 103 m, to have a safety margin. Given the inflow hydrogram and the objectives, Bedam has to return a set of maneuvers that fulfils the objectives, or state that there are no maneuvers. For this episode and the initial configuration, BeDam proposes the maneuvers shown at the top of Figure 4 that consist of opening the two intermediate outflows with the pattern shown. The bottom half shows the corresponding evolution of the dam level (green line) and the outflow (magenta line). Clearly, both magnitudes satisfy the constraints over time.

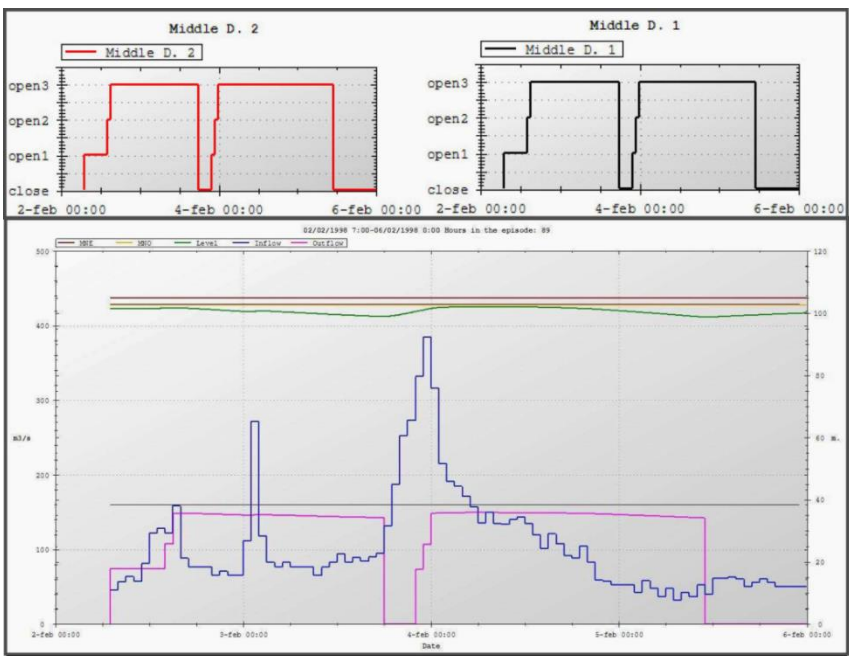

Figure 4 Maneuvers suggested and dam evolution

CONCLUSIONS

In this paper we have presented a DSS which uses formal methods to perform simulations and optimizations of dam management. Compared with traditional discharge policies, BeDam not only indicates the water discharged over time but, also produces the set of maneuvers that said discharge achieves. In [5] we explored the suitability of SPIN for the synthesis of dam controllers, and now, here, we have improved upon this previous approach to obtain a complete DSS that implements different discharge policies and suggests operations for fulfilling objectives as a single tool. We have implemented the model of a real dam and we have used a historic flood episode to calibrate the different models.

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