Gebhardt, Michael; Schmitt-Heiderich, Peter; Wohlfart, Sven

Automated operation of chains of barrages – development of controller algorithms with the use of model-based design

River Flow 2010 - Dittrich, Koll, Aberle & Geisenhainer (eds) - © 2010 Bundesanstalt für Wasserbau ISBN 978-3-939230-00-7

Automated operation of chains of barrages - Development of controller algorithms with the use of model-based design

M. Gebhardt & P. Schmitt-Heiderich
Federal Waterways Engineering and Research Institute, Karlsruhe, Germany

S. Wohlfart
Institute for Hydromechanics, Karlsruhe Institute of Technology, Germany

ABSTRACT: The operation of barrages has different restrictions and usage requirements to be observed such as hydropower, navigation or flood protection. Against this background the automatic flow and water level control of barrages is a sophisticated control task due to the non-linear behavior of the process and the multi-purpose use of the impoundment. The paper describes the use of Model-Based Design (MBD) as a method to design and simulate controller algorithms on the basis of unsteady flow simulations and by using graphical modeling tools. A MBD approach allows the designer an early verification and validation of the controller. In addition, special cases in operation can be analyzed and the impact on the impoundment can be assessed. The workflow is presented from requirements to implementation at barrages at the federal waterways. Moreover it is shown, that the automation of chains of barrages creates new demands and requires a coordinated flow management and control in order to ensure a moderate discharge to optimize the hydropower and to provide sufficient water depth for navigation.

Keywords: Automation, Barrage operation, Controller algorithm, Unsteady flow simulations

1 INTRODUCTION

Germany has a wide-meshed, economically powerful system of waterways with a total length of about 7350 km, of which 24 % are cannels, 35 % free-flowing and 41 % impounded rivers. For these the Federal Waterways and Shipping Administration (WSV) operates 290 weirs in order to control the water level and the discharge. In most cases, power plants are located next to the weirs. One example is the barrage Lehmen (Figure 1) that spans the Mosel River with a height of about 7.5 m.

Figure 1. Barrage Lehmen with power plant, weir and ship lock at federal waterway Mosel

It consists of a power plant with a capacity of 20 MW at a discharge of 400 m³/s, three 40 m wide and 5.4 m high sector gates and a 12.0 m wide lock chamber with a useful length of 170 m. The barrage Lehmen is one of 28 barrages in the 394 km long navigable part of the Mosel River between the mouth of the river at Koblenz and the French city Neuves-Maisons. Ten barrages are on German and two on German-Luxembourg territory (Table 1).

Table 1. Length, height and volume of the Mosel River impoundments on German or German-Luxembourg territory

Dam	length [km]	height [m]	volume [10^6 m³]
Palzem	12.1	4.0	4.6
Grevenmacher	17.1	6.3	7.4
Trier	17.0	7.2	9.6
Detzem	29.2	9.0	21.3
Wintrich	25.4	7.5	15.4
Zeltingen	17.5	6.0	9.5
Enkirch	20.9	7.5	11.5
St. Aldegund	24.7	7.0	12.1
Fankel	18.8	7.0	9.6
Müden	22.3	6.5	11.0
Lehmen	16.3	7.5	8.9
Koblenz	18.9	5.3	7.5

As part of the renewal of the drive machinery, the technical equipment of the twelve weirs has been replaced. In this course the current water level controller was replaced with a modern discharge and water level control system. The automation of the weirs was aimed at supporting the shift personnel and to improve the quality of water management. Today, all weirs, except Koblenz, are modernized and equipped with local controllers, which were developed and parameterized by the Bundesanstalt für Wasserbau (Federal Waterways Engineering and Research Institute (BAW)).

2 MODEL-BASED DESIGN

Model-Based Design (MBD) is a methodology of addressing problems associated with designing complex control systems and is applied in designing embedded software.

The first step is choosing a mathematical model for the impoundment, the weir and the power plant. Based on these mathematical models, control algorithms can be designed on the computer and analyzed. Thus the impact on the operation of the waterway can be identified and special cases in operation can be safely tested (second step).

The algorithms were initially developed and tested in proprietary programming languages. For data processing, visualization and evaluation of results self-developed and commercial programs were used. The developed algorithms must be adapted in practice to pass vendor-specific programmable logic controllers (PLCs). This process is time consuming and error prone, since the implemented code is hard to read and has to be tested through an extensive validation.

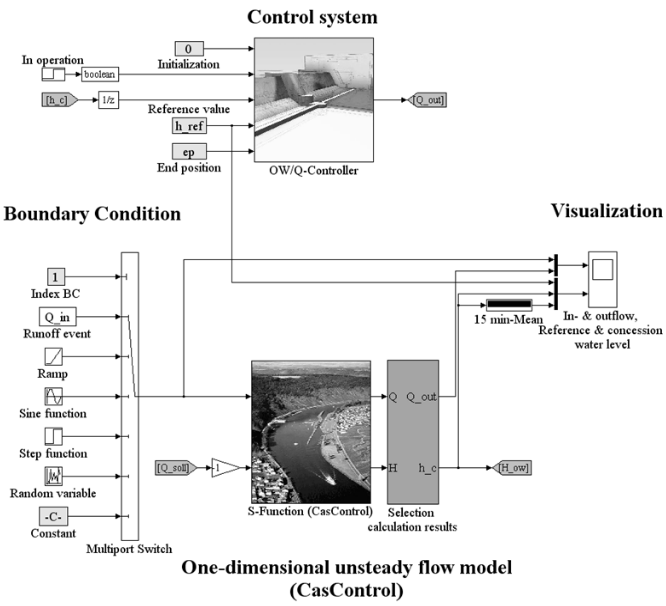

Figure 2. Simulink-Model with control system and one-dimensional unsteady flow model (CasControl)

In this paper, a relatively new development is presented, which generates an executable code on a target platform from a model published (third step). For this purpose the interactive environment MATLAB & SIMULINK (www.mathworks.com) is used, which provides a hierarchical modeling using graphical blocks (Figure 2). In addition, an own code can be integrated into the model with S-functions. The created models are much clearer than the usual code and can be executed without compilation.

The development process of automatic code generation is presented in Figure 3: On the one hand, system description, modeling up to coding (step 1 to 3) and on the other side test and integration on the target (step 4 and 5). The mathematical model of the controlled system (impoundment) and the actuator (weir, power plant) provides the basis for the controller design (Wohlfart & Gebhardt 2009).

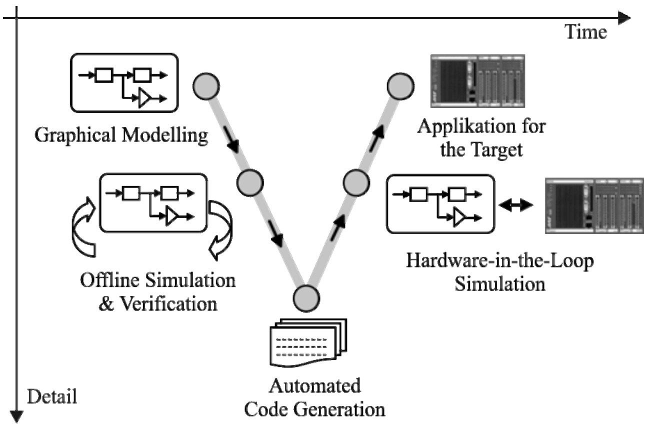

Figure 3. The V-model of a software development process

3 MODELING

3.1 *Impoundment*

If y is the response of a controlled system to the input signal u, and k*y is the answer to k*u, then the system is called linear, for which many well-established analysis and design techniques are available. In contrast, impoundments show a nonlinear behavior that varies over the control range. Hence, a one-dimensional unsteady flow modeling system is the method of choice.

Cross-sections are extracted at each 50 to 100 m distance in the flow direction and used for the model input. In the BAW the in-house software CasControl is used, which is a compiled version for use with MATLAB & SIMULINK on basis of the modeling system CasCade+. With the help of an implicit solution procedure, CasCade+

solves the dynamic motion equation of de St. Venant for a network structure.

$$\frac{\partial}{\partial t}\begin{pmatrix} A \\ Q \end{pmatrix} + \frac{\partial}{\partial \xi}\begin{pmatrix} Q \\ Q^2/A + P \end{pmatrix} = \begin{pmatrix} q \\ g\,A\,S_\xi - g\,A\,S_f \end{pmatrix} \quad (1)$$

The formulation of de St. Venant describes the process behavior, where A is the wet cross section of the river bed, Q is the flow and P is the total pressure on A depending on the time t and the position ξ. The lateral inflow is denoted by q. The frictional slope S_f , which depends on the bottom structure, is calculated by the Manning formula and S_o is the bottom slope (Bleninger et. al. 2006).

3.2 *Weir and power plant*

In the model of the actuator weir, alongside the characteristic curve of the gates, the weir schedule, the driving speed, the minimum and maximum step size and the lower and upper end position are considered. With the help of the characteristic curve of the gates the setpoint discharge determined by the controller can be converted into a setpoint position of a gate and vice versa.

Figure 4 shows an example of the weir Grevenmacher, which consists of two sector gates. The characteristic curves of the gates were determined with a laboratory model.

Gebhardt & Schmitt-Heiderich (2008) present that modeling the weir cannot be neglected for the controller design, since the gates show a slower response compared to the turbines, leading possibly to the fact that a new setpoint position cannot be reached in the next cycle step.

3.3 *Control algorithm*

The authorities impose conditions on the operation of power plant and weir, which usually imply keeping the concession level as close as possible to a reference level, in this case within the limits of ±0.05 m. The control of the reference water level constitutes a control problem where the controller manipulates the discharge. The difference between the measured value (concession level) h_c and the reference value h_{ref} is the error and acts as input to the controller.

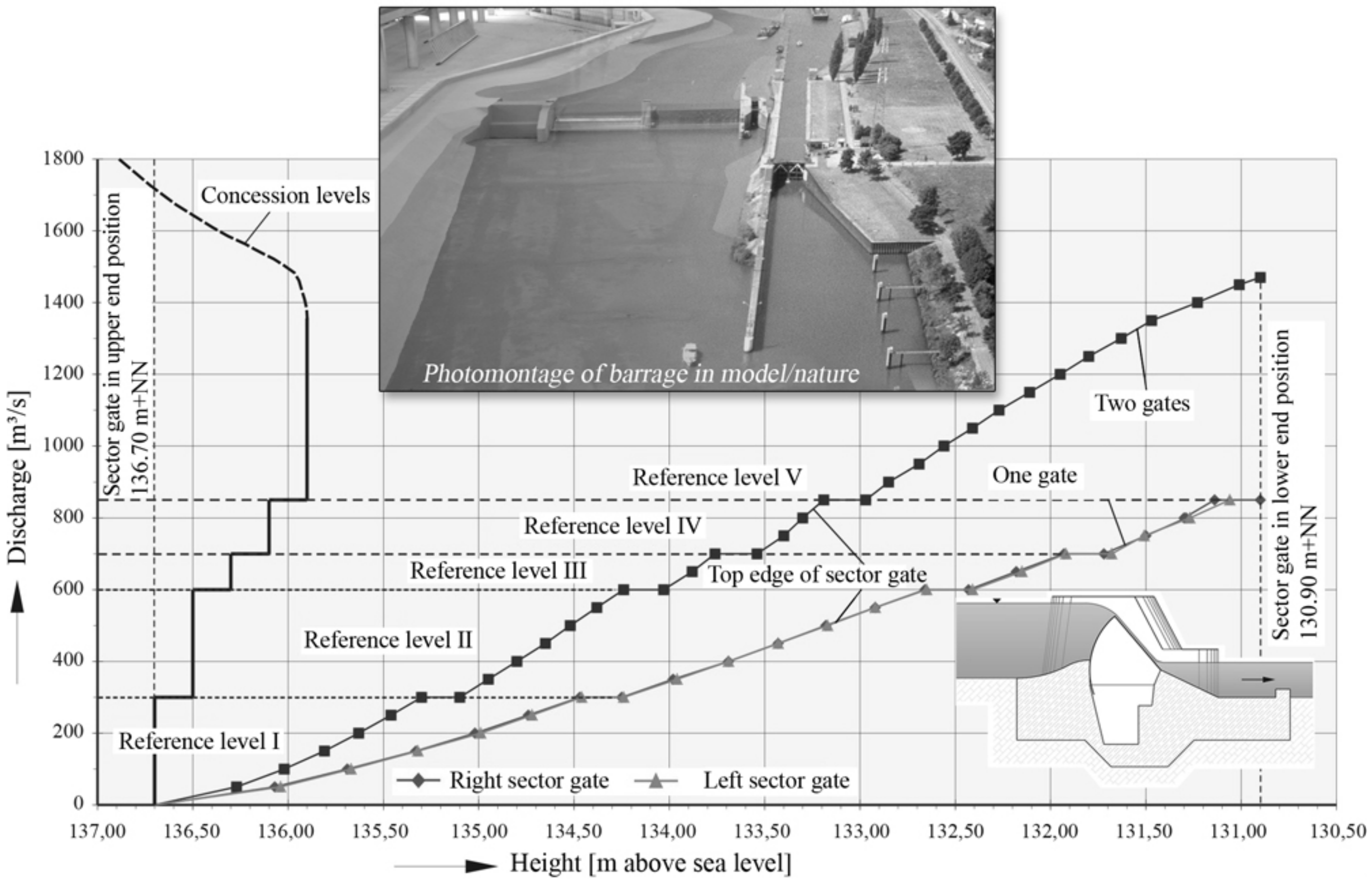

Figure 4. Weir Grevenmacher - Characteristic curves of the gates on the basis of a laboratory model, photomontage of the dam in nature und model.

For impoundments that are prone to overshoot, a so-called OW/Q-controller is state of the art.The scheme of the controller is shown in Figure 5, in which OW denotes the upper water level (process variable h_c) and Q the inflow of the impoundment (disturbance variable Q_{in}).

While the water level control is carried out with a classical proportional-integral (PI)-controller (control term), the disturbance variable is taken into account through a filter and a dead time element (feedforward control term). Thus the OW/Q-control is a mode of operation, in which the water level control and flow control are connected.

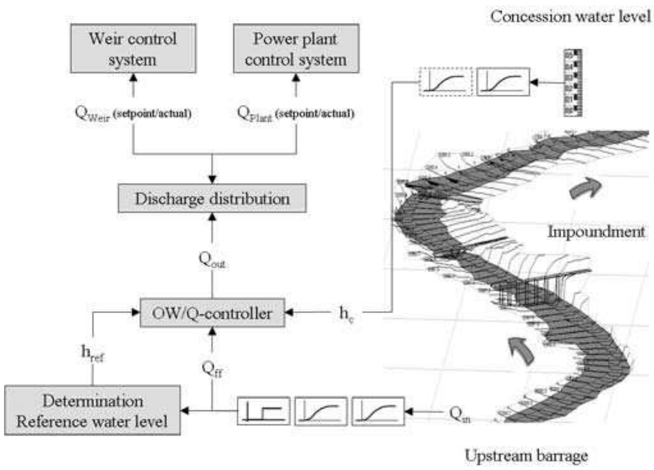

Figure 5. Structure of the OW/Q-controller at the example of the Mosel River impoundments

In control theory parlance it is referred to a closed-loop controller with a feedforward control on the actuator.

$$Q_{out}(t) = Q_{ff} + k_P \cdot \left[\Delta h(t) + \frac{1}{T_I} \cdot \int \Delta h(t) \cdot dt \right] \qquad (2)$$

with Q_{ff} = feedforward term, Q_{out} = outflow of the impoundment, Δh = control error and T_I, k_P = parameter of the PI-controller respectively.

4 DETERMINATION OF THE CONTROL PARAMETERS

4.1 *Analysis of the impoundment*

With the help of a simulation it can be shown very clearly in which discharge range the impoundment tends to overshoot. For this purpose a cascade inflow function is set as the upper boundary condition and the outflow is calculated at a constant upper water level. The time between the inflow steps is chosen so long, that a steady state condition is reached again.

Figure 6 shows simulation results of the impoundment Fankel. Up to an inflow of 200 m³/s a larger outflow step can be seen for a given change in the inflow, while for greater inflows the respond of the impoundment is very "kindly". Another possibility is to characterize the properties of the impoundment by the propagation time T_L and the retention time T_R as described i.e. in Neumüller & Bernhauer (1969).

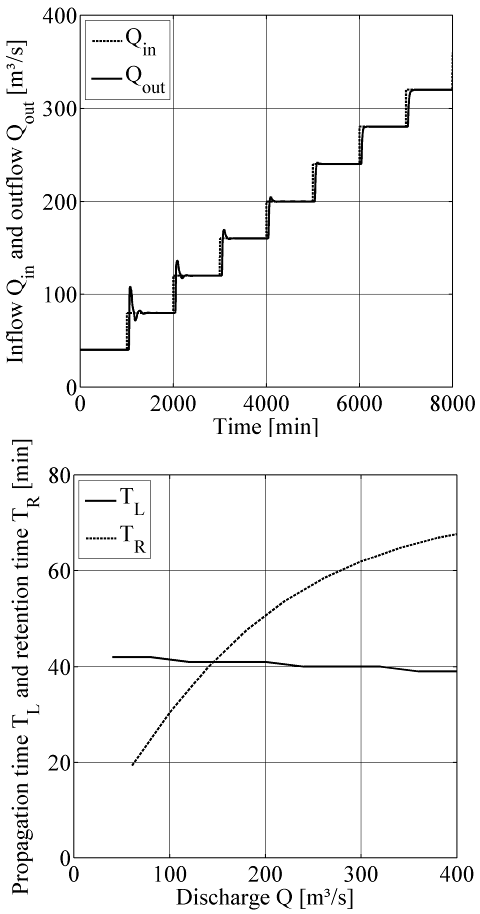

Figure 6. Step response, propagation and retention time of the Mosel River impoundment Fankel

The proportion of the feedforward control is parameterized in such a way that the inflow will be delayed by the amount of the retention time. Here, T_R is the time that is needed to store or to leave a difference in water volume, so that a new stationary water level can be reached at an inflow change from Q_1 to Q_2. T_R can be calculated from the capacity curve of the impoundment ($T_R = \Delta V/\Delta Q$) and depends on the discharge.

In Figure 7, the capacity curves of eleven Mosel River impoundments and the resulting retention times are shown. The discontinuities mark the change in the reference value where the storage volume is reduced. The comparison shows that each impoundment must be parameterized individually.

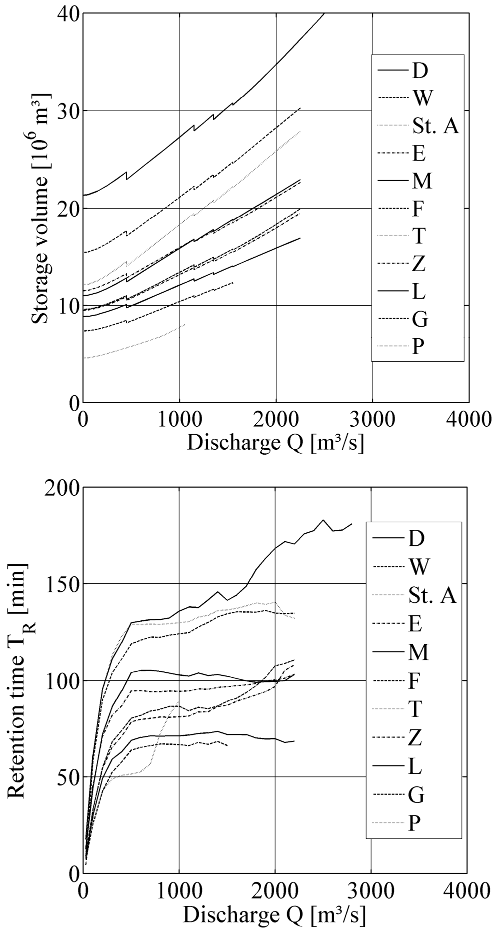

Figure 7. Capacity curves and resulting retention times of the Mosel River impoundments

4.2 *Parametrization of the feedforward term*

Typically, the retention time is divided into a dead time and a series of low pass filters, which lead to a smoothed output with a variation superimposed input signal. But in addition to smoothing, low pass filters also cause a phase shift, which corresponds to the filter time at a gradually varied change of inflow. Thus the following simplified relationship exists between the retention time T_R, the dead time T_D and filter times T_F of the low pass filters Theobald (1999):

$$T_R \approx T_D + 2 \cdot T_F \tag{3}$$

The influence of dead time and filter time can be demonstrated in the response of the OW/Q-controller to a sudden and to a continuous change in inflow (Figure 8): A large filter time and small dead time effect a stronger smoothing in case of sudden changes in flow. In another case, the inflow is also delayed by the retention time T_R, but the filter times are shorter and the resulting dead time is longer. The damping is not as strong in case of sudden changes and the feedforward control is later, although the sum of dead time and filter times is the same in both cases.

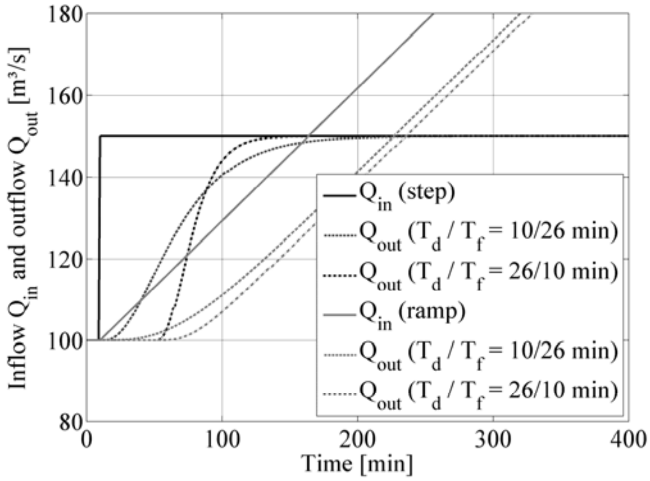

Figure 8. Step response of the feedforward control term to a sudden and to a continuous change in inflow

Finally, it is necessary to analyze the feedforward control in conjunction with the water level control term: Figure 9 shows the response of the OW/Q-controller, upstream water level and outflow, to an inflow wave, which results from a drawdown operation upstream of the Mosel River section under consideration.

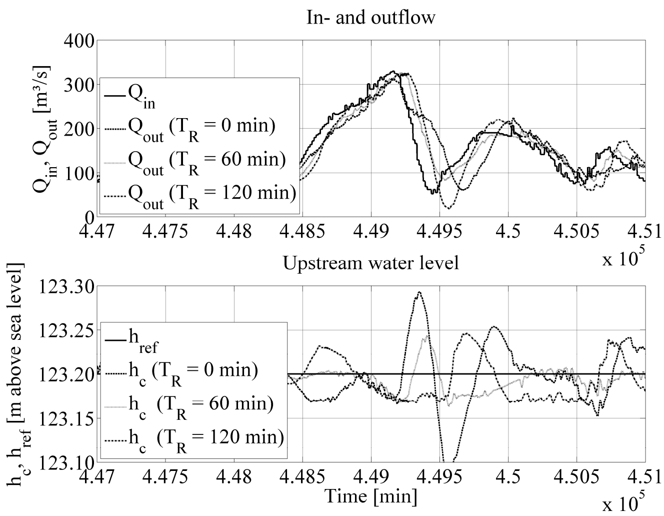

Figure 9. Step response of the OW/Q-controller Detzem to an inflow wave with different parameters of the feedforward control

If the proportion of feedforward control is too early in the controller output, the outflow increases also too early, which leads to a drop in the upstream water level below the reference value. The proportion of control will act against. At the time of arrival of the wave peak, the outflow is lower than required, with the result that the reference level is exceeded. The integral term is built up and causes a time-delayed increase of the outflow. This is evident in the change in the characteristics of the flow curve in the descending branch.

The later the feedforward control is present at the controller output, the later is the increase in outflow resulting in a dropping water level and in an increasing negative integral term. Through the overlay with the decreasing proportion of feedforward control the minimum of discharge will be strengthened.

This example shows, that a rapid feedforward control effectuates a positive dampening effect on the discharge fluctuations and a negative overshoot with respect to the upstream water level. The ratio is reversed, if the proportion of feedforward control is too late.

4.3 *Parametrization of the control term*

To determine the parameters of the PI-controller, proportional gain K_P and integral time T_i, inflow steps (test functions) are applied around a base flow and the effects on the controlled system are analyzed without the feedforward term. This analysis is repeated at different flow levels. Since different parameter combinations lead to similar water level variations, additional criteria have to be taken into account such as variability of water level variations, damping of the discharge variations, number of control commands, etc. All criteria will be normalized to a uniform scale and weighted combined into one overall assessment. By systematic variation the parameter range can be evaluated for its suitability.

In Figure 10 four evaluations of individual criteria and the weighted and normalized criteria versus the parameters are shown exemplarily (Schmitt-Heiderich 2009). It can be seen that the choice of a "good parameter" differs fundamentally at specific criteria (the arrow indicates the direction, in which the control performance improves). Also, among the criteria, there are no clearly identifiable optimal parameters but only areas of suitable parameter combinations. Finally, the overall assessment replaces not a verification of the specific criteria.

4.4 *Simulation of real runoff events*

In addition historical runoff events of different durations and characteristics are simulated for the evidence of control parameters. The runoff hydrographs for the simulation were available in time steps of 15 minutes. Figure 11 shows an example of a simulation result for a 12-Day event regarding in discharge variations, number of control commands (adjustments) and deviation of the reference level. As the frequency distribution shows, the reference level was almost entirely held in a range of ±0.05 m. Display of the moving gates provides on one hand information about the overall load for the drive units and indicates on the other hand the operation of the controller.

During the specific period of 12 days there has been almost 340 adjustments of gate 1 and 2 compared to 150 adjustments from gate 3. This leads on an average of 1.2 adjustments per hour only.

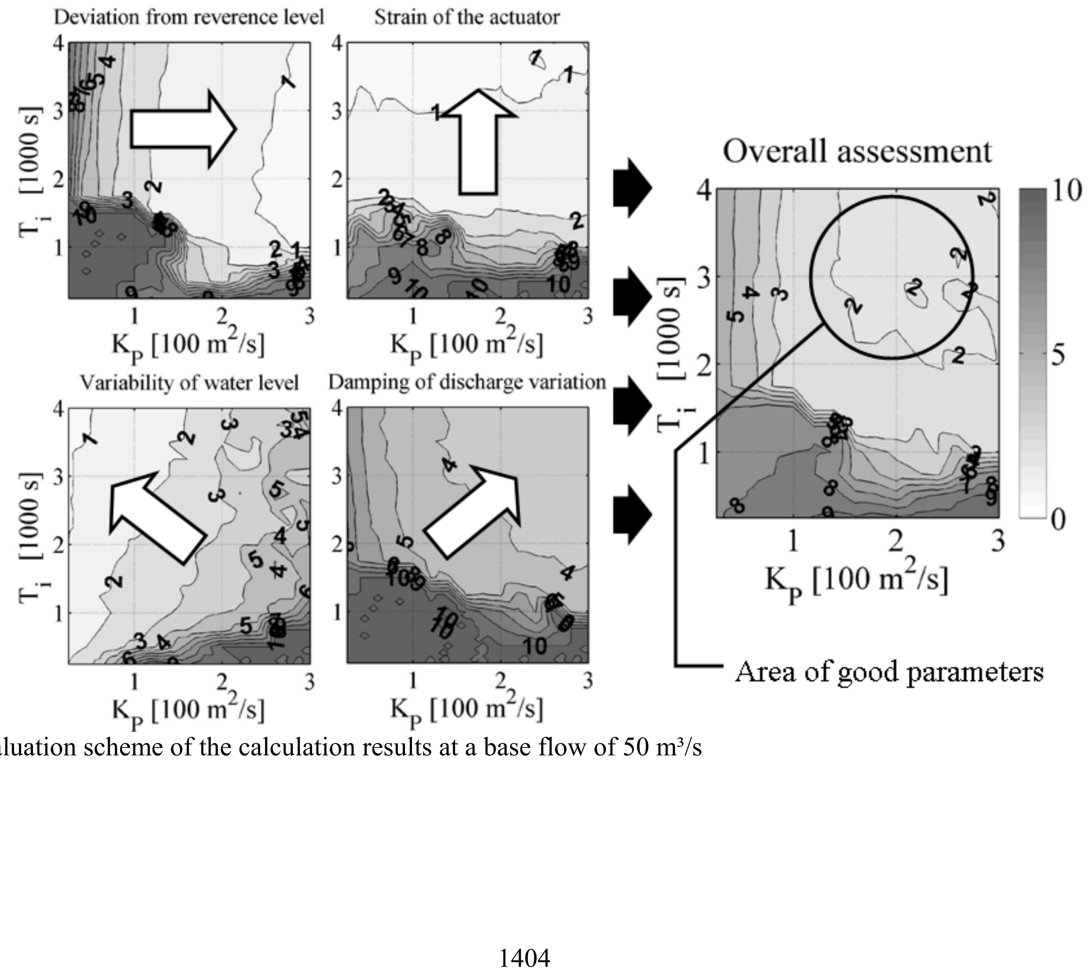

Figure 10. Evaluation scheme of the calculation results at a base flow of 50 m³/s

A comparison of the controller performance in different time periods regarding the deviation of the reference level yields to different qualities. Figure 11 shows relative frequency distributions of the error based on 1 min values for three selected months: October 2007 is typical for a low or mean water period (MNQ = 59 m^3/s) with the discharge only through the turbines. April 2008 represents a mean water period (MQ = 315 m^3/s) where the discharge goes through the turbines and up to two gates. Finally March 2008 is a mean to high water period. (HQ1 = 1280 m^3/s) where temporarily all gates are in operation for flood discharge.

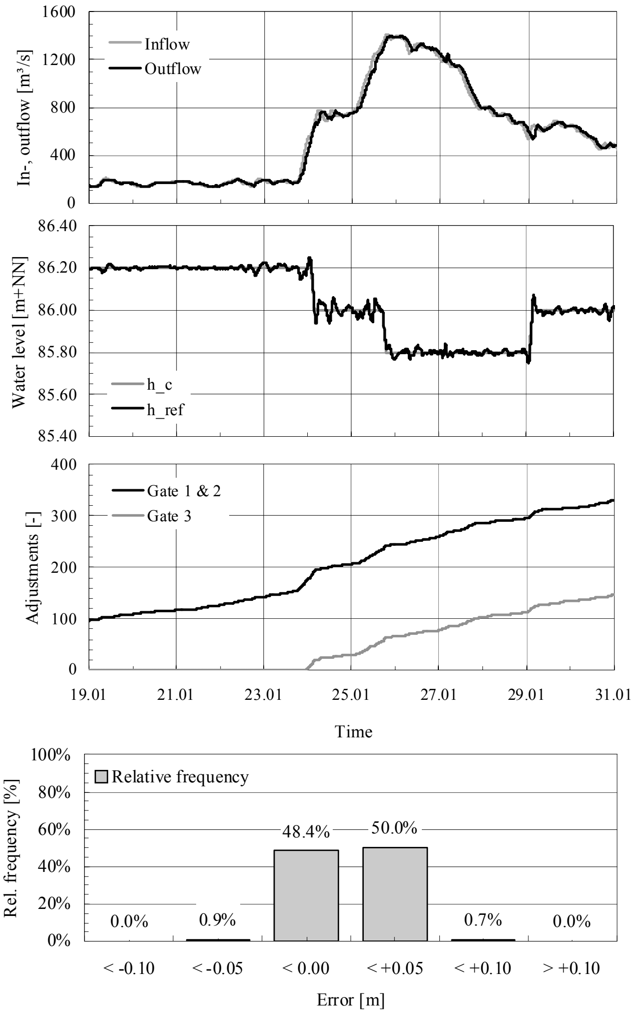

Figure 11. Simulation results of the automated Mosel barrage Fankel

Several things can be noticed from Figure 12: First, the reference level was almost entirely held in the limits during three months, however with different scattering. In October 2007, the concession level was kept less strictly within the limits as in the two other periods. The controller response appears faster than during flood discharge. This is due to the influence of the actuator: As the turbine follows every change in the controller output, gate reaction is slower. Less but greater shifting steps cause greater fluctuations in the headwater level.

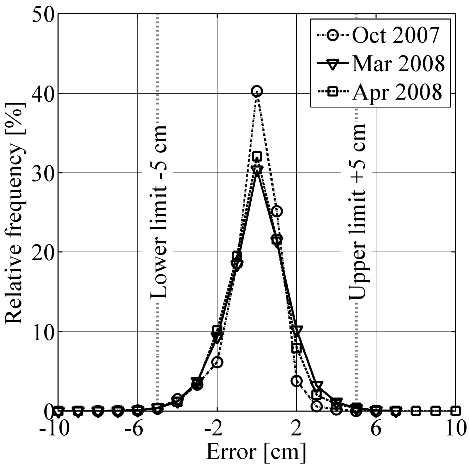

Figure 12. Deviation of the concession level of Mosel barrage St. Aldegund - Relative frequency distributions of the months October 2007 (Q = 20÷220 m^3/s), April 2008 (Q = 290÷820 m^3/s) and March 2008 (Q = 300÷1350 m^3/s)

5 PRACTICAL ASPECTS

5.1 *Operational experiences*

At the barrages of the Mosel River operational experiences are partly available for several years with mainly positive results. Thus, an analysis of the automatic operation and a first control of success is possible. The evaluation of the controller performance refers not only to the concession levels up- and downstream or gauging stations, but also to all variables of the OW/Q-controller. The control system on-site records data which can be displayed in diagrams or exported for further processing.

To increase the acceptance for the automation and to improve the understanding of the control behavior in special situations, trainings are carried out for the operational staff. Therefore, the numerical model of the impoundment was connected to a programmable logic controller (PLC) by an OPC Server. This process is also referred to as Hardware-in-the-Loop (HiL) and is often used by the automotive industry.

With the help of this real-time system several specific case studies could be demonstrated in the training sessions including emergency shut-down of a turbine, flow reduction due to rake cleaning, shifting of the reference water level, reaching end positions of the gates or filling the impoundment in low water periods. The visualization capabilities have been real-time presentations of the impoundment and the weir (Figure 13). With regard to turning on the controller it could be shown that under unsteady conditions the safest way is to operate manually until the outflow corresponds approximately to the inflow. Error should also be as small as possible, but even at differences up to ±0.05 m the time until the controller settles at its target value is less than 1.5 hour (Gebhardt & Wohlfart 2008).

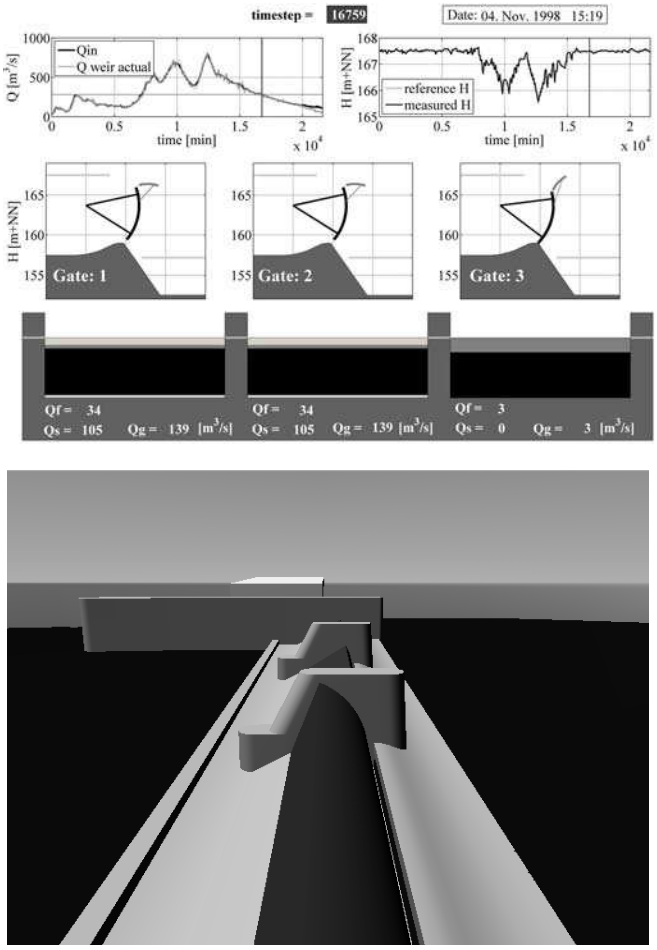

Figure 13. Visualization examples: Radial gate with upper flap gate (above); Virtual Reality Model (VRML) of a sector gate (below)

5.2 *Applications for automatic code generation*

An increasing number of companies offer PLCs with software tools for automatic code generation. For this purpose, templates for the Simulink Extension Real-Time Workshop are available, that are specially adapted for proprietary hardware. The portability of controllers that have been developed with the help of Simulink, has already been tested in BAW's laboratory using a water tank model.

The first practical application will be a supervisory controller for the first three impoundments of the Mosel River. Here the control objectives are defined with focus on discharge damping regarding the relevant inflows and taking advantage of the available storage volume (Theobald 2010). After analyzing the available gauging stations in the catchment area, the development of optimization strategies and the comparison of the simulation results with real data, the supervisory controller will be implemented on a M1 controller system by Bachmann electronic in 2010.

6 CONCLUSIONS

For the automation of impoundments methods and tools are used in the BAW, that allow the design, the systematic optimization of parameters and the testing of control algorithms. Negative effects for shipping can be avoided in advance and ensure the maintenance of traffic. After commissioning, it is important to monitor the automated operation, e.g. by a remote access to the system: On the one hand for control of success and quality assurance, and on the other side to verify the models and to adjust selected parameters in deviant behavior in model and nature.

To increase the acceptance by the operating staff, training is beneficial in situations, where special operations can be presented in real-time using hardware-in-the-loop simulations. Perspective, software tools are gaining importance, where automatic implementation of control algorithms on the hardware side is enabled and Model-Based Design is supported.

REFERENCES

Bleninger, T., Fenton, J.D., Zentgraf, R. 2006. One-dimensional unsteady flow modelling for compound channels: case study of a river junction and wide flood-plains of the River Rhine, River Flow 2006, Sept. 6 - 8, 2006, Lisbon, S.1-10.

Gebhardt, M.; Schmitt-Heiderich, P. 2008. Entwicklung und Simulation von Regelungsalgorithmen für Staustufen an Bundeswasserstraßen. Wasserwirtschaft, Heft 6/2008, S.16-18.

Gebhardt, M.; Wohlfart, S. 2009. Erste Erfahrungen mit der Umsetzung der automatisierten Abfluss und Stauzielregelung an der Mosel. BAW-Brief Nr.1, Heft 6/2008, S.6-11.

Neumüller, M.; Bernhauer, W. 1969. Stauregelung und Abflußregelung an Laufwasserkraftwerken". Die Wasserwirtschaft 10. S. 297–303.

Schmitt-Heiderich, P. 2009. Modellgestützte Festlegung von Regelungsparametern. BAW-Brief Nr.1, Heft 6/2008, S.1-5.

Theobald, S. 1999. Numerische Simulation von Staustufenketten mit automatisiertem Betrieb. Institut für Wasserwirtschaft und Kulturtechnik, Mitteilungen 201, Universität Karlsruhe.

Theobald, U.; Theobald, S. 2010. Central water resources management in a cascade of hydropower plants, First IAHR European Congress, May 4 – 6, 2010, Edinburgh.

Wohlfart, S.; Gebhardt, M. 2009. Reglerentwurf und automatische Codegenerierung. BAW-Brief Nr.1, Heft 6/2008, S.11-16.