Decision support system for Iron Gate hydropower system operations

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Abstract: Today, hydropower systems operate in highly competitive environment. Thus, it is important for them to get maximum benefits out of existing assets, resources and constraints as well. In order to make the best possible operational decision in complex hydropower system, it is necessary to consider as many scenarios as possible. Decision makers would benefit from a system that allows them to analyze a large set of possible scenarios and choose the most suitable one under current circumstances. In this paper, a decision support system for hydropower system operation applied to the Iron Gate hydropower plant is presented. This is modern, model-based system which connects data management, physics-based numeric model as well as optimization algorithms applied to developed model. The implementation of the entire system was carried out through the development of software solutions dedicated to Iron Gate power plant needs. Scenarios of everyday use are presented as well.

INTRODUCTION

One of the important characteristics of electric power systems is that at practically all times generation and consumption of electricity must be equal. At the same time, load of electric power systems is highly variable in time (to meet the needs of a large number of diverse consumers, whose needs change in time in different ways – in daily, weekly, monthly or seasonal terms). On the other hand, it is necessary that all elements of the system operate with a high degree of beneficial effect (i.e., in their optimal mode, or close to it), so that production costs can be reduced to a minimum.

Various forms of uncertainty occur during the power system operation. One of the reasons for this is that certain parts of the system may not be available at a certain point in time, and neither the system load nor power consumption can be fully predicted on daily basis. Therefore, continuous and quickly available reserves and capacities for power regulation in the system must be provided.

Hydropower plants are easier manageable than other power generating plants. In the case of power plants with large reservoirs, it is possible to generate electricity with almost arbitrary dynamics, which is not the case with, for example, wind turbines. This is one of the most important features of using hydropower potential, which is not present in any other method of electricity generation.

However, in complex market conditions with the increasing presence of intermittent sources of renewable energy and various existing limitations (currently available quantities of water, impact on other water users, etc.), the benefits of hydropower can only be achieved with optimal planning and operational management of hydropower facilities. Optimal management of hydropower systems, and in particular large-scale hydropower systems, which are often cross-border, is a major challenge. Optimal management requires to develop and implement complex decision support systems.

Decision support systems are information systems whose purpose is to provide assistance in expert decision-making in the implementation of a series of activities related to the planning and management of hydropower systems. Such systems solve a number of tasks through automated processes that are important for decision making, such as: data integration, data analysis, simulation, optimization, data processing and visualization, etc.

Making optimal management decisions using different optimization techniques is a topic that has been extensively discussed in the literature analysing various priorities and specificities of the system [1,2]. In [3], a monthly optimization model for large-scale system is developed. Decision-making framework for frequent condition changes of hydropower system is discussed in [4]. In addition to this, the economic aspect of the application of such systems is also important. The timing adjustable short-term model aimed at optimizing the system's operation so that the highest profit is achieved, which can certainly be one of the main criteria when making a operational decision, is shown in [5]. On the other hand, the growing electricity demand often requires the hydropower system to operate at full capacity during the peak consumption period. Subject operational mode can be optimized using expert knowledge and dynamic programming techniques [6]. The operational planning of the system is based on a meteorological forecast that incorporates a certain degree of uncertainty. [7] presents a multi-criteria short-term planning model in which the uncertainty of the weather forecast is evaluated and corrected accordingly.

A medium-term decision support system with a linear optimization model is shown in [8]. The aim of optimization is to maximize profit by monitoring the electricity price forecast, the current inflow, all with respect to the preset environmental constraints.

Decision support systems with data management modules i.e., implementing the principle of data integrity are described in [9,10]. The [9] presents the general objectives, background, problems, and main components that a single decision support system in the field of hydro-potential management should contain.

In the Serbian hydropower system, hydro power plant system (HPP) Iron Gate is the most important system for hydropower generation in Serbia, because it covers 50% of total hydropower production, i.e., 22% of total power production. The Iron Gate hydropower system consists of two hydropower and navigation systems "HPP Iron Gate 1" and HPP Iron Gate 2 built on the joint Serbian-Romanian sector of the Danube. Also, it directly affects the level of the Danube River along more than 300 km.

In view of the above, a few years ago the Institute embarked upon the complex task of developing decision support system (DSS) for HPP Iron Gate operational planning and management. The paper presents the structure of the system and several technical solutions that were necessary to solve such a complex task.

HPP IRON GATE

HPP "Iron Gate 1" (Figure 1 – left) consists of the main facility, reservoir and riverbank area. The main facility – "Iron Gate 1" dam, 1278 m long, is symmetrically divided into Serbian and Romanian parts, each consisting of: ship lock, embankment non-overflow dam, hydro power plant with 6 units and concrete overflow dam. The concrete gravity overflow dam occupies the central part of the profile and consists of 14 spillway bays, which, in addition to turbines and other evacuation bodies, allow the evacuation of the return discharge of 10,000 years, which is 22 350 m3/s.

The HPP "Iron Gate 1" reservoir was formed on a complex river system, consisting of the Danube and its tributaries: Tisza, Sava, Velika Morava, Tamiš, Nera, Mlava, Pek and Porečka Rivers. A significant characteristic of the "Iron Gate 1" reservoir is the variable length of the backwater and pool size, as a function of the discharge and mode of operation of the hydropower plant. At high waters, the backwater stretches up to the mouth of the Nera River (km 1075), while at low waters, the backwater elongates to Novi Sad on the Danube (about 310 km long), up to Šabac on the Sava River (about 100 km long) and Tisza up to the dam at Novi Bečej (about 60 km long).

***Figure 1**. HPP Iron Gate 1 and HPP Iron Gate 2*

The "Iron Gate 1" reservoir bank area has different characteristics, which determine both the size of the impact and the method of protection. The downstream part of the reservoir on the Danube is in the Đerdap Gorge, so there is no backwater impact on the riverbank, except in some sites (built-up main road, high banks). Upstream from Golubac, the reservoir stretches through the plain area, so that the mode of the hydropower plant operation impacts external, internal and groundwater. Consequently, water level constraints on characteristic profiles have been introduced.

HPP "Iron Gate 2" (Figure 1- right) is the downstream step of the system working in a coupled mode with HPP "Iron Gate 1". HPP "Iron Gate 2" consists of main facility, reservoir and riverbank area. The main facility consists of two dams, on the main course of the Danube and on Gogoš, with hydropower plants and ship locks. Two hydropower plants with 8 units each are located on the dam. The overflow dam is in the middle of the profile with 7 spillway bays, while a Serbian 34 m wide lock and an additional hydro power plant with 2 units are closer to the right bank. The Romanian lock is located on a channel through the island of Mare. The overflow with 7 spillway bays is in the middle of the profile on the dam in the Gogoš effluent, while a Romanian additional hydro power plant with 2 units was built along the right bank of the effluent.

The "Iron Gate 2" reservoir is made of 80 km long Danube riverbed. At maximum levels, the volume of a reservoir is 820 million m^3 and reservoir has no significant tributaries.

The bank of the "Iron Gate 2" reservoir is flat, thus the water regime is formed under the influence of the hydropower plant operating mode. Consequently, operational restrictions have been introduced.

Rational management of complex HPP systems "Iron Gate 1" and HPP "Iron Gate 2" implies simultaneous fulfillment of requirements set by power systems of Serbia and Romania, which differ in terms of power and time, including compliance with a number of restrictions on control profiles on the Danube defined by interstate documents. The operation of the HPP "Iron Gate 1" and HPP "Iron Gate 2" is regulated by internal rules between Serbian (Public Enterprise Electric Power Industry of Serbia) and Romanian (FE Portile de Fier) companies, which were adopted at the intergovernmental Yugoslav-Romanian Mixed Commission during 1998.

DECISION SUPPORT PLATFORM FOR IRON GATE HYDROPOWER SYSTEM

A significant role of HPP Iron Gate in the power system of the Republic of Serbia, as well as a number of benefits that can be achieved by proper management of such a large and complex system, but also on the other hand, a significant number of potential undesirable effects, both short-term and long-term, that can occur due to improper management, have for many years pointed out to the need for the development and implementation of a HPP Iron Gate planning and management support system. There are several problems in practice when the decision support system can play a significant role [11]. Problems range from daily operational planning and generation monitoring, through long-term analysis of operations and setting all parameters subject of procedures defined by interstate documents, to the management of the system in emergency conditions (high water, ice, major equipment failures, etc.). The Jaroslav Černi Institute has conceptualized, designed, developed, and implemented a complex information system to support decision-making in the planning and management of the HPP Iron Gate system. The system is designed to be used for solving several problems. This paper will focus on supporting operational planning and system management.

Operational planning and management of the hydropower cascade of HPP "Iron Gate 1" and HPP "Iron Gate 2" implies meeting the requirements of the Serbian power system with a balanced distribution of hydro-potentials together with the Romanian side, meeting a number of restrictions on control profiles on the Danube that guarantee both the provision of navigation conditions and the stability of the riverbanks. Also, the operation of the "Iron Gate 2" system was directly conditioned by the operation of the "Iron Gate 1" system.

The operational planning procedure involves defining the hydropower generation schedule at the start of the energy day for the period of the next 3 to 5 days, to make the best use of the available water potential in the context of current priorities, based on the available hydrological forecast. Relying on the daily plan, operational management implies monitoring the operation of the cascade at the hourly level and continuous verification of compliance with the needs of the power supply system.

To optimally plan and operationally manage production, a support system was formed consisting of several software components (databases, services, etc.), physically based mathematical models, optimization modules and web-based user tools (Figure 2).

The observability of the cascade is based on the correct operation of an extensive monitoring system that monitors the levels along the reservoirs and tributaries, the levels in the dam zone and the operation of hydropower units and appropriate hydro machinery (positions of gates, etc.). Major spatial distribution (hundreds of kilometres), the pronounced temporal imbalance in sampling (from daily to minute step) and the pronounced heterogeneity of measuring and acquisition equipment resulting from decades of the monitoring systems development, have conditioned the innovative approach to the data management system implementations. As the data are coupled with a mathematical model without the involvement of an expert, it is required that the data management system also implements automatic mechanisms for assessing the quality of the available data [12].

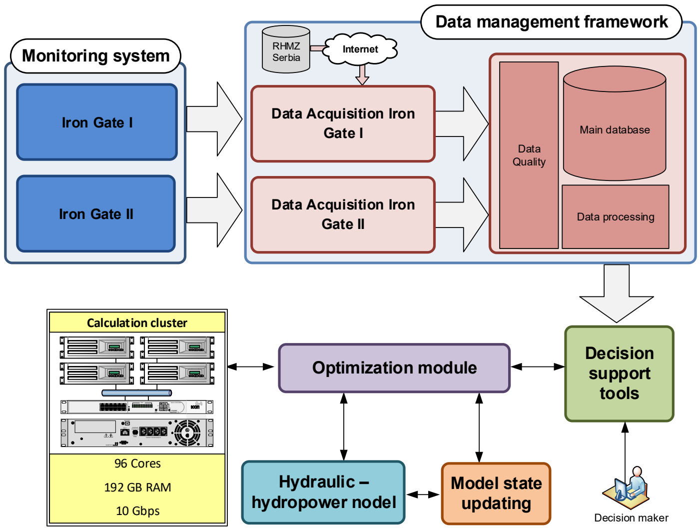

Figure 2. *Decision support platform architecture for Iron Gate hydropower system*

The central part of the system is an extensive 1D coupled hydraulic-hydropower model that describes at a high level of detail the unstable movement of water coupled with all relevant processes of transformation of hydropotential into electricity. To use the model effectively for the plan verification, it is necessary to bring the computation state close to the realized, i.e., to establish a connection between the observed data and the result of the simulation in the period of the previous 7 days. Assimilation of the observed data is carried out in a computation efficient manner by implementing a new approach based on control theory [13, 14]. As defining the optimal plan in practice is a multi-criteria optimization problem, the system has an optimization module that effectively forms a set of Pareto optimal solutions. Web-based user tools have also been developed to monitor the optimization process, but also to quickly select the most favorable plans from the formed Pareto set. This paper provides more details below about each of the mentioned subsystems.

MONITORING SYSTEM

The monitoring system of the Iron Gate hydropower system consists of a wide set of measurements that monitor the state of facilities, hydro-mechanical and electrical equipment, as well as the hydrological situation upstream and downstream of the reservoir and on the riverbank. The basic characteristic of these measurements, in addition to the diversity of measurement values, is the redundancy of the source, and pronounced spatial distribution. The monitoring system provides data for routine operation and maintenance at the powerplant, but only selected data is used for scenario analysis and management decision making. For such data, the platform defines a framework for data management that provides a common model for data storing. The data required for making the management decision include water levels on rivers, water levels at the dams, data on the hydropower unit operation, as well as data on the spillway operation. The largest number of measurements are located at the power plant facilities, while hydrological level measurements on rivers are located along the main course of the Danube and larger tributaries on both the Serbian and Romanian sides (Figure 3).

Water levels along the river course are observed at several hydrological stations. Republic Hydrometeorological Service of Serbia (RHMSS) manages 6, while the other part of the stations was purpose-built for Iron Gate hydropower system monitoring.

Data from 6 RHMSS stations are obtained through bulletin service. The purpose-built stations are managed by HPP Iron Gate (10 stations in total) and FE Portile de Fier (12 stations). Hydrological stations are equipped with a redundant water level measurement system consisting of 2 or 3 instruments, to increase the reliability of the measured values.

Water level measurement is also performed in the vicinity of following dams: Iron Gate 1 and 2 and the Gogoš dam, as well as in the zones of the intakes and outlets of HPP Iron Gate 1 and HPP Iron Gate 2.

Two independent SCADA systems are in use at both Iron Gate 1 and 2, one for Serbian part of the dam, and the other for Romanian part. All instruments at the dams are measured redundantly, being wired to both SCADA systems separately.

Data on water levels are collected and archived in those SCADA systems, as well as data on the hydropower unit operations: discharges through the hydropower units, head and tail water levels on the hydropower units, active and reactive power.

Electricity generation is recorded in the ABB power meter database, while the official values of dispatching services are recorded in the Oracle database. Data on the spillway operation include the openings of the spillway and the time of operation.

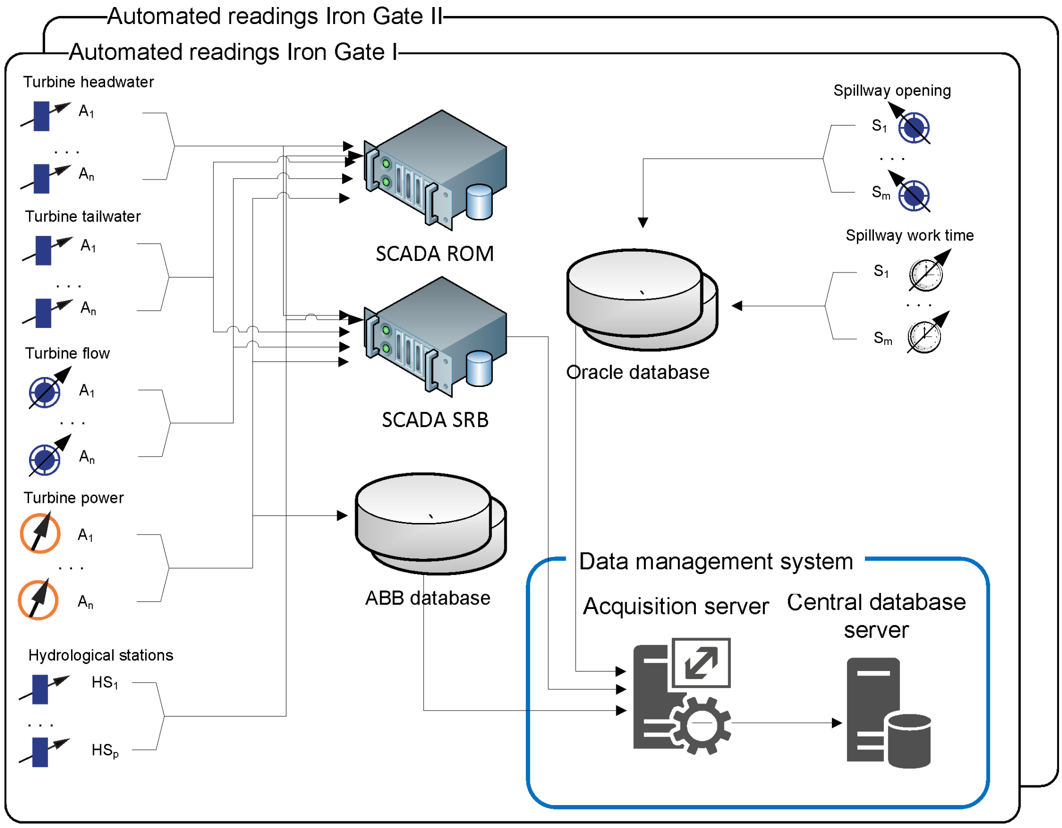

***Figure 3**. Monitoring schematics of Iron Gate hydropower system*

DATA MANAGEMENT FRAMEWORK

Data management framework (DMF) is part of the decision support system providing data warehousing. The basic problem regarding presented monitoring system is heterogeneity of data formats and regularity of data. Most measurements are usually automated by SCADA systems, or dedicated software solutions of the measuring equipment manufacturer, and a minor part is the subject of manual reading. Establishing an operational framework requires a common data model that will be used throughout the system, also including the level of confidence in terms of the accuracy of the value (data quality). The basic elements of the DMF are:

- Data Acquisition
- Data Archiving
- Data Quality Control
- Data Processing.

Data Acquisition

The monitoring system is constantly evolving over time by introducing new measuring stations, upgrading equipment and communications. This results in the introduction of new data sources and means of data delivery and storing. Thus, some data are available as hourly or daily reports in the form of text files, others are stored locally in databases, while others are available via the Internet.

Data acquisition is the process by which measured data are retrieved from various sources within the monitoring system, validated and sent to a central database. To retrieve measurements from the monitoring system, the ETL approach [15] is used, implemented through appropriate modules that are regularly executed. ETL is a widespread method in data data integration and consists of three steps: Extraction, Transformation and Loading. The modules are designed to be flexible in terms of expansion and refinement, robust so that they can overcome certain problems in interpreting the measured values independently, and fast so that the data processing does not take too long. Also, to simplify implementation and maintenance, one module instance processes multiple files from a single source, using different arguments.

Upon receipt, all data is validated, after which it is stored in the local data storage. The result of validation is data status that may be either appropriate or inappropriate. This is one way the measured data is filtered and allows the rest of the system to continue to work only with the appropriate data.

The data stays in the local storage until it is transferred to the central server, after which data is truncated after defined period. This is how the local storage serves as the time-limited redundancy of the collected data on the central server.The data transfer mechanism from the acquisition server to the central server is centralized and uniform, thanks to a data transfer layer that retrieves data from the local storage and then forwards it to the central server.

Each ETL module starts independently, according to the frequency of measurements. Table 1 shows the average number of acquired measurements during one day per each module.

Table 1. *Average number of data acquired in one day*

Measurement type	Iron Gate I	Iron Gate II
Data on levels on rivers and in the zone of facilities	~1,200	~1,600
Data on the hydropower unit operation	~46,000	~21,000
Data on the operation of spillways	~2,000	~1,500

Data Archiving

The central database is designed as a warehouse for observation data within DMF, amounting to about 27,000,000 on an annual basis. The data is stored in a central database in the form of time series, in order to simplify the analyses carried out on the collected data. The database supports the monitoring of data changes and the possibility of expert correction, while keeping the original data. A special segment in the database is dedicated to the measuring system, whereby changes in the measuring system are set to be monitored (for example, changes in the reference elevation, sensor replacement, etc.), in order to enable a more accurate interpretation of possible problems in the data.

The central database was implemented as a relational database. Data is exchanged with the rest of the system through the layers in the form of services. This is how the access to the central database is completely managed through system-based access management mechanisms, while the other layers and tools in the system do not have direct access to the database.

Data Quality Control

Validation process of the data collecting rejects measurements that are physically inappropriate (e.g., outside the scope of the instrument) and such data automatically receive a quality grade 0. More complex quality assessment techniques must be applied to other data to determine their usability in the system due to problems that normally occur when performing measurements. Examples of such problems are given in Figure 4 when the water level on the left changes suddenly in a short period of time then remains constant, while the water level on the right has an instant dip in the measured values. All values shown are within the measuring range of sensors, however, as these values usually change slowly (due to the inertia of the system), the presented measured values may be deemed unreliable. The need for reliable and timely data for use in simulations requires automated procedures for data quality control.

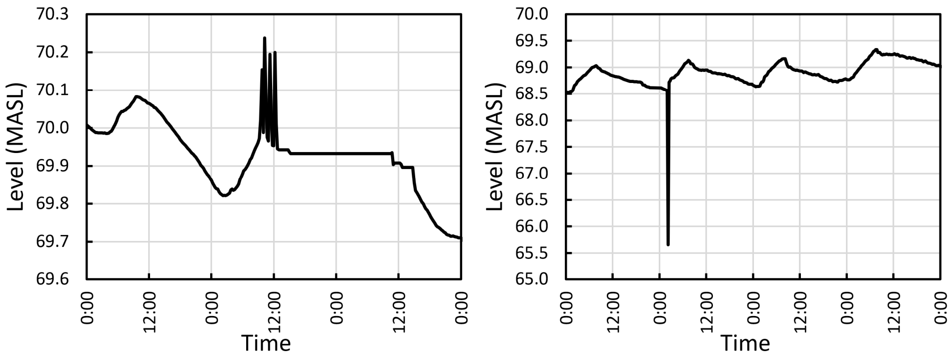

Figure 4. *Example of poorly measured data*

Data quality control is implemented in the process of archiving data, in such a way that the data becomes available to the rest of the system as quickly as possible [16].

When determining data quality, the following attributes are assigned to each data:

- quality grade (range 0-1);
- measure of the quality grade reliability (a measure of the dispersion of the set of quality grades that participated in the formation of the final quality assessment) and
- scheme or list of methods used to perform the quality control.

The grade is formed based on the application of specific methods within the technical data quality control schemes. The set of schemes envisaged for a particular series is grouped into a quality assessment formula [12].

In addition to the quality grade, each data piece is assigned a reliability grade for the quality grade depending on the method of quality control.

Schemes for the data quality control are a set of methods, arranged in a flexible structure with the basic condition that one of the methods requires only the data parameter that is controlled and the time of measurement (among other meta-data). The schemes are formed in such a way that the methods are executed hierarchically [17], i.e., that with the increase of available additional data and information, more methods for data quality control are executed [36].

Data Processing

Data collected through the acquisition, controlled and stored in a central database, are available to the rest of the system in their original form or processed according to a specific request. Data processing includes application of analytical functions, data aggregation (averaging, summation, etc.) and value composition.

A value composition is a way of processing data under which one value is selected from a set of multiple time series per assigned criterion: priority or data quality. The priority criterion uses multiple time series in the processing chain, each of which is a lower priority than the previous one. This is how it is possible to use the values of time series obtained from different sources or the value of the same variable from another (nearby) location. The quality criterion ensures that the system always works with the data that has the highest level of reliability at that moment.

HYDRAULIC-HYDROPOWER MODEL

The mathematical model for hydropower calculations and management of exploitation of the system "Iron Gate 1" and the system "Iron Gate 2" is a model of water movement in a large and complex area, which includes: water inlet to the system, open-channel flows, overflow on the spillway facilities on the dams and flow and energy generation at hydropower plants [18].

The model includes a section of the Danube River from Novi Sad up to the mouth of the Timok River - 408.65 km long. Tributaries, on the subject section of the course are Sava, Tisza, Velika Morava, Tamis, Mlava, Pek, Poreč River and Nera. Based on the geometric data processing, the course of the Sava River (from the mouth up to the HS Sremska Mitrovica, 138.5 km long) and the course of the Tisza River (from the mouth up to the HS Senta, 120.8 km long) have been adopted to be included into the model as tributaries. Other tributaries are characterized by the geometry of the river course that is disproportionate to the Danube River course, which is why the influence of these tributaries is considered through the given inflow at the mouths. The whole model is shown on Figure 5.

The model consists of river sections which modeled 1D open-channel flow and control facilities (dams, control profiles, couplings) connected with those sections. Model boundaries are defined by external boundary conditions, while connections between facilities and river sections are defined by internal boundary conditions [19]. External boundary conditions are set at all points that represent the inlet or outlet from the model (upstream and downstream boundary conditions) as well as at places where the water stage or hydrographs are known. The applied internal boundary conditions are the boundary conditions of the fork and mouth type and the boundary condition of the dam type.

The internal boundary condition of the dam type defines the discharge through the dam facility that occurs as a result of the power plant and the spillway operations and affects the unstable flow in the system. This boundary condition permits setting of control values that affect the operation of the model.

The basis of the software implementation of the hydraulic-hydropower model is the open-source hydraulic computation software FEQ (Full Equations) [20]. Solving the system of non-stationary flow equations in open-channel flows is based on the application of the finite difference method that enables setting internal boundary conditions. This feature of FEQ was used build in the models of hydropower facilities in the solver for hydraulic computations. The extension of the basic FEQ software was implemented through special modules to facilitate the analysis, modification and extension of the code.

The model is divided into 20 river sections with a total of 617 profiles. There are a total of 11 external boundary conditions: 3 upstream (Danube, Sava, Tisza), 7 at the mouths of non-modelled rivers (Velika Morava, Tamis, Mlava, Nera, Pek, Porečka River, Kolubara) and 1 downstream (Timok mouth). The internal boundary condition of the fork and mouth type is set at a total of 12 locations (5 of the fork type and 7 of the mouth type). The boundary condition of the dam type was applied to 3 locations (Iron Gate 1, Iron Gate 2, Gogoš).

Execution of the model within hourly time step, for a computation period of 7 days, on Intel Core i7 configuration and 16 GB RAM, takes 10 seconds and only 2MB of operating memory.

MODEL STATE UPDATING

The purpose of the hydraulic-hydropower simulations is to predict the state of the system for the next few days (usually 3 to 5 depending on forecast availability) from now on, for different scenarios of hydro-potential use. One of the most common problems that occurs in this case is the inconsistency of the initial conditions (model state) with the actual situation in the field (measured values), which increases the unreliability of the forecast results. All this ultimately affects poor management decision making and suboptimal system operation.

Data assimilation is carried out by combining available observations with a background state from the numerical model, to find the best estimate of the current state of the system. Then, updated model is used to run a short-term forecast and the output of which is background state for next data assimilation cycle. Such method relies on assumption that, for any location, there are continual and reliable data. If the reliability of the measured data for a location is high, then the model state is updated according to the measured values at that location. Otherwise, the model state does not change as the measured data is ignored due to high unreliability.

The decision-making process in the Iron Gate hydropower system is most influenced by the uncertainty in assessing the inflow of the Danube, as well as poor inflow estimates on significant tributaries such as Sava, Tisza and Velika Morava. As system operation decisions are made daily, the use of the model requires assimilation that would bring the model state closer to the actual state in a relatively fast period [37].

The largest number of assimilation methods is based on the application of the Ensemble Kalman filter (EnKF), which are statistically based methods. However, these methods have proved not to be suitable for real-time application purposes [14], so other techniques need to be investigated. One of them is indirect approach in which model results are corrected based on the measured data by changing another value. The correction of model parameters shown in [21, 22] is applicable to the unreliability of model parameters, but it is necessary to use standard assimilation methods again, which brings back the mentioned problem of time consumption. The methodology presented in [23, 24] was developed for the drainage system in urban areas and is based on the addition and subtraction of a certain water quantity obtained based on the difference between the measured and computed water level. The approach presented in [24] is the model improvement where the input to the model is not concentrated in one place but has several locations. Nevertheless, the methodology is concentrated on urban drainage systems and is not directly applicable in hydropower systems.

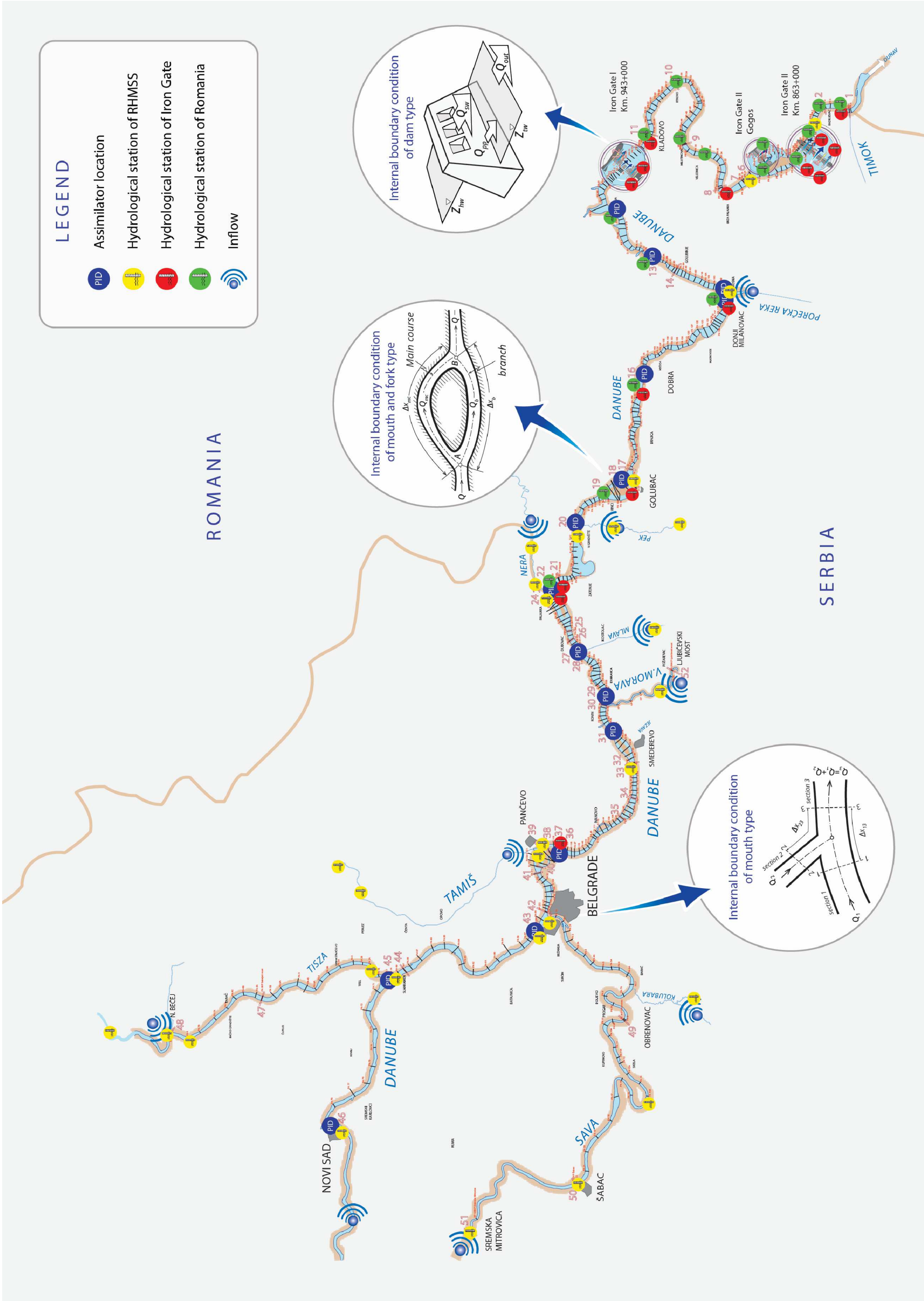

Figure 5. *Model structure*

The application of control theory and PID controllers proved to have some strengths over other methods [25, 26], primarily in terms of the simplicity of PID controllers as well as the results obtained by comparison with classic assimilation methods [13].

According to this method, the corrective inflow applied to the specific node of the model is determined based on the difference between the computed and measured level.

$$\Delta Q(t) = K_P \cdot e(t) + K_I \int_0^t e(\tau)d\tau + K_D \frac{de}{dt} \qquad (1)$$

Assimilator locations are shown on Figure 5. In places where there is a high probability of measuring noise (noise in the measured data), it is not recommended to use a member that depends on the error change rate, so $K_D=0$ and PID becomes a PI controller. The integral in the equation is calculated by the trapezoidal rule for numerical integration and the derivative by the finite differences. By applying the PID (Figure 6) controller, the rate of correction is gradually changed by adjusting the required value with the possibility of "faster" operation if the differences in the expected and computed state are large.

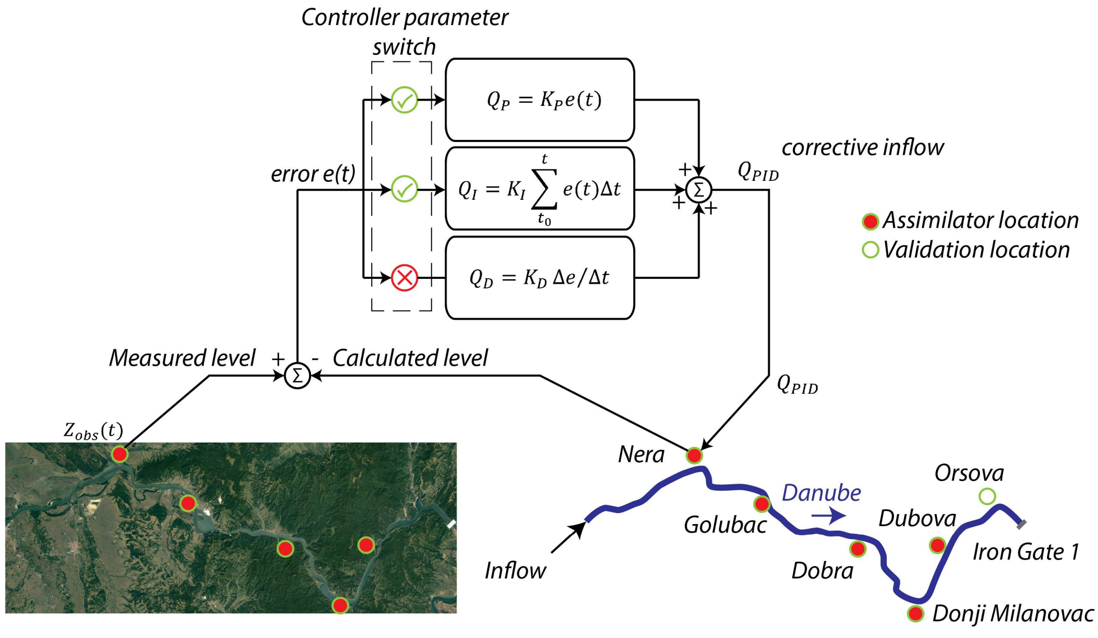

Figure 6. *Assimilator with PI(D) controller*

The error that is the input to the PID controller is computed as follows:

$$e = \frac{1}{N}\sum_1^N \varepsilon_i C_i = \frac{1}{N}\sum_1^N \left(h_{M,i} - h_{R,i}\right) * C_i \qquad (2)$$

where $h_{M,i}$ is the measured level, $h_{R,i}$ is the computed level, and C_i is the quality rating. For redundant measurements: N>1. The aforementioned methodology of level correction implies the existence of measurements in each computation step, to adjust the model state in each step to the observed values. In reality, one cannot expect the continuity of measurements with such a high frequency, and even if so, it is realistic to expect occasional cancellations and lack of measurements. For this reason, in addition to the confidence in the measurement resulting from technical quality C, a confidence based on the time elapsed since the last available measurement was introduced:

$$T(\tau_m) = \begin{cases} & \tau_m \le f_s \\ 1 - \left(\tau_m \frac{1}{0} f_s\right)/f_d & f_s < \tau_m \le f_s + f_d \\ & \tau_m > f_s + f_d \end{cases} \qquad (3)$$

where τ_m is the time elapsed since the last measurement, f_s is the time period since the last measurement during which the confidence in the measurement does not decline, and f_d is the period after the expiration of f_s during which the confidence in the measurement gradually drops to zero.

$$e = \frac{1}{N}\sum_{1}^{N} \varepsilon_i C_i = \frac{1}{N}\sum_{1}^{N}\left(h_{M,i} - h_{R,i}\right) * C_i * \tau_{m,i} \tag{4}$$

The correction of the level in the model is done using a special internal boundary condition that permits the addition or subtraction of the discharge. After the change, the model itself propagates the entered change upstream and downstream by computing the changes along the entire section of the Danube.

OPTIMIZATION MODULE

Problem definition

The operation of the Iron Gate hydropower system is designed on one hand, to meet the pre-set scheduling of hydropower and at the same time does not violate the exploitation constraints on the upstream and downstream part of the Danube. The physical and structural limits of equipment and facilities must be also considered.

Optimal hydro unit commitment at the hydropower plants Iron Gate 1 and Iron Gate 2 implies determining the power to be realized at all power plants, so that the resulting discharge at the power plants expend the minimum hydropower potential, and that the power plants generate the maximum revenue. In addition, the optimal hydropower unit engagement plan should ensure compliance with the operational constraints and the minimum number of hydro unit starts. Therefore, the problem of forming a several days scheduling for HPP Iron Gate is a problem of multi-criteria optimization. The solution to the problem is a set of Pareto optimal solutions, from which, based on additional information, a compromise solution is chosen that cannot be optimal according to all criteria. Discovering many optimal compromise solutions provides the possibility for decision makers to consider what is gained and what is lost with each of them and, by considering at a qualitatively higher level, to make a choice of one solution.

The following input values are used to formulate the optimization problem (for whole forecasting period):

- Inflows forecast (with the possibility of setting the uncertainty of the inflow into the reservoir)
- Market electricity price each hour of the same period
- Availability of hydro units and spillways.
- Operational constraints.

Optimization goals are defined by optimization criteria:

- The first criteria are generating the maximum total income on the Serbian and Romanian sides, according to the forecasted hourly electricity prices for the period.
- The second criteria are minimization of the consumption of available hydro potential, i.e., maximizing the remaining hydro potential. Optimization according to this criterion is performed indirectly by maximizing the mean daily elevation at the mouth of the Nera River into the Danube in the last hour of the optimization period.
- The third criteria are the minimization of the risk of violating the exploitation constraints of the water level in the system

The result of the optimization is hydro unit commitment on hourly basis. Optimal unit commitment is achieved via internal optimization of generation at the level of individual power plant units.

Algorithm Solving

The previously described problem of multi-criteria optimization with mutually conflicting criteria is successfully solved using multi-criteria genetic algorithms [27]. The advantage of applying multi-criteria genetic algorithms is the fact that they work with the entire population of possible solutions so that, during one execution, they can find a whole set of Pareto optimal solutions. The ability to simultaneously search different part of the solution space provides for finding a wide set of solutions for complex problems as well.

The optimization module implements the NSGA-II algorithm as one of the commonly used genetic algorithms in the literature to solve multicriteria optimization problems [28, 29, 30]. NSGA-II stands for Non-Dominated Sorting Genetic Algorithm, i.e., an algorithm based on sorting non-dominated solutions. The advantages of applying this algorithm is non-dominated sorting techniques which provide the solution as close to pareto optimal as possible as well comparative operator based on crowding distance providing diversity in solution [31].

To solve the optimization problem using the NSGA-II algorithm for multi-criteria optimization, it is necessary to perform encoding of unknown values in the form of realistically encoded chromosomes. Each chromosome is composed of a series of genes so that the first n*4 genes in a series represented *n* hourly power of the unit through each of the 4 power plants, one for each hour of the period for which the plan is being developed (Figure 7). In the case of a three-day optimal unit commitment plan, one chromosome has 288 genes.

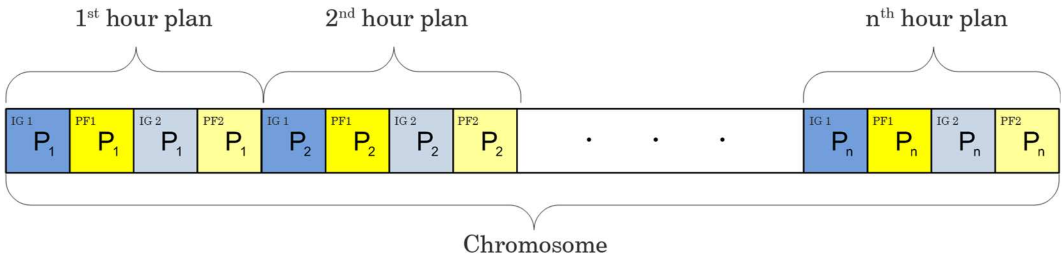

Figure 7. *NSGA-II chromosomes*

In accordance with the specified optimization criteria, the following goal functions have been set:

- Goal function of maximizing revenue from electricity generation. Revenue is calculated by multiplying generation in each hour by the forecast price in the same hour.

$$F_1 = \max\left(\sum_{k=1}^{N}\left(E_1^k + E_2^k\right)c_k\right) \tag{5}$$

- Goal function of minimizing the consumption of available hydro-potential. The state of reservoir at the end of the subject period is estimated through the value of the mean elevation in the last 6 hours of the computation period on the profile at the Nera mouth. This value is maximized in the optimization process, thus ensuring the minimization of the consumption of hydro potential.

$$F_2 = \max\left(\frac{1}{6}\sum_{i=N-5}^{N} Z_i\right) \tag{6}$$

- Goal function of risk minimization. The risk is assessed as the distance from the limit violation. The greater the distance from the violation, the lower the risk. Any plan that achieves a distance from a violation that is greater than a certain value (tolerance level), the rating is zero. The risk rating increases as the distance from the tolerance level to the violation decreases. For plans that violate limits, the risk rating rises sharply with increasing violation.

Genetic algorithms are parallelized to shorten the execution time [32, 33]. The basic idea of parallelizing the algorithm is to divide the entire job into sub-tasks that can be run in parallel on multiple processors, with the aim of speeding up the execution of the algorithm, while not impairing the quality of the results.

The result of the optimization computation is the "Pareto" front of optimal plans of hydropower plants engagement in the system. The decision as to which plan will be selected is left to the expert who, in the given circumstances, should assess which of the criteria will be favoured as decisive and thus choose a compromise solution.

Software Implementation

Generating and evaluating many scenarios requires significant engagement of computer resources as well as the time required for execution. The implementation of the solution requires the existence of a mechanism for distributed evaluation independent of the computing platform [34] as well as a flexible allocation of available resources in accordance with the level of complexity of the problem being solved.

The numerical optimization module was implemented through the purpose developed WoBinGO software platform [35] specifically designed for these types of support system. This platform consists of (Figure 8): a software component for elastic allocation of distributed computing resources (Work Binder) and a library of evolutionary algorithms (JARE).

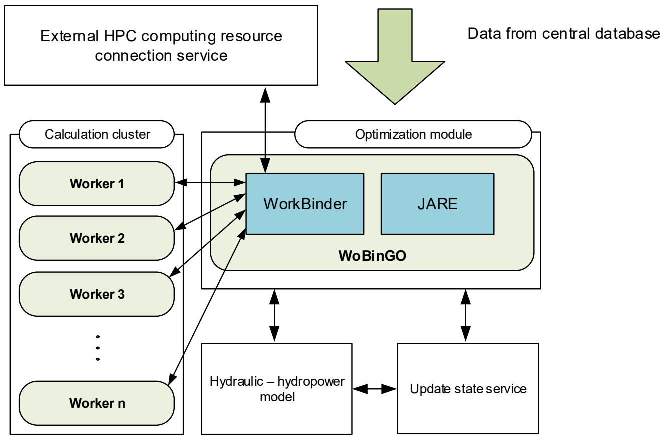

Figure 8. *Optimization module architecture*

The Work Binder service provides almost instant access to distributed resources such as a computation cluster and increases their utilization by automatic and elastic occupation, depending on current and recent client behavior. This service can dynamically allocate both external computation resources through HPC providers and services for connection to external computation resources.

JARE is an object-oriented library of classes developed using .NET C# of languages, which provides a flexible and scalable collection of evolutionary algorithms and associated components required for their implementation.

DECISION SUPPORT TOOLS

The decision support platform possesses user tools that use the hydraulic-hydropower model and optimization module, along with data from the central database and forecasts (hydrological and financial). The dispatchers can monitor the behavior of the Iron Gate 1 and 2 systems and analyze the effects of management decisions in recent periods, as well as in the near future. The user tools that provide operational support to the electricity generation and trade in regular operation conditions will be presented in more detail below. A special set of tools provides management support in high water conditions.

The user tool for operational support of electricity production and trade at the level of the “power day” (from 6:00 AM on the current day to 6:00 AM on the following day) is intended for solving a certain set of characteristic problems related to electricity production planning and trade: verification and optimization of the production plan aligned with the operational data on the electricity prices, distribution of hydropower potential in accordance with the operating rules and compliance with constraints in the implementation of daily plans.

The tool provides a flexible way of modelling the operation of the FE Portile de Fier, while respecting its’ specific role in the Romanian power grid, which is significantly different from the one that "Iron Gate" has in Serbian power grid. This makes it possible to evaluate the optimality of the system operation in a way that is as close to reality as possible.

This tool provides analyses that consider the reliability of hydrological analysis and uncertainties in forecasting electricity prices. The results of the subject analyses provide a positive impact in establishing a multi-day optimal plan, i.e., they increase confidence in the attainability and optimality of the production plan in complex and dynamic conditions of the electricity market. In addition, the tool also has mechanisms for automatic creation of reports on the previous system operations, as well as forecasted conditions (hydrological and market) and estimated optimal plans of hydropower unit engagements.

The computation of the previous period includes functionalities the user can engage to obtain information on the values of measured hydrological and exploitation values, as well as the reconstruction of values that cannot be obtained by direct measurements but are the result of the computation of the hydraulic-hydropower model. In this sense, the most important information is the one on division of hydropower potential between the Serbian and Romanian sides, but also an assessment of the inflow into the reservoir and volume changes in the reservoir. The Serbian and Romanian parties may use this data to agree about any disputed issues related to the exploitation of hydropower potential.

As regards to the part dealing with forecasted values, the planning services use the forecasted electricity prices from the exchanges to form an optimal production plan for the power day. On the other hand, dispatchers at hydropower plants can check the production plans for the power day with the same tool, which includes the plan variation option based on the Romanian side's request. Namely, the alignment of the production plan between the Serbian and Romanian sides is a daily activity, whereby it is possible that the plans obtained from the production planning services are not aligned, so adjustment is necessary. Since in this sense it is often a redistribution of planned hourly production, without affecting the total daily production, this tool allows to perform checks or generate a new optimal plan according to the corrected implementation dynamics. It is also possible to check the effects of the proposed plan on the following days, since a multi-day forecast of the inflow into the reservoir is available.

The input data formation and the parameter setting required for plan optimization is simplified in the tool, so that users can easily select the options to set the appropriate optimization problem and send it for solving. The user receives the result of the optimization computation as a set of optimized plans, each of which is better against the other one according to one of the optimization criteria, but is worse against others according to another criterion. This is called a "Pareto" front of optimal plans for the hydropower plants engagement in the system. The decision as to which plan will be selected is left to the user who, in the given circumstances, should assess which of the criteria will be favored as decisive and thus choose a compromise solution.

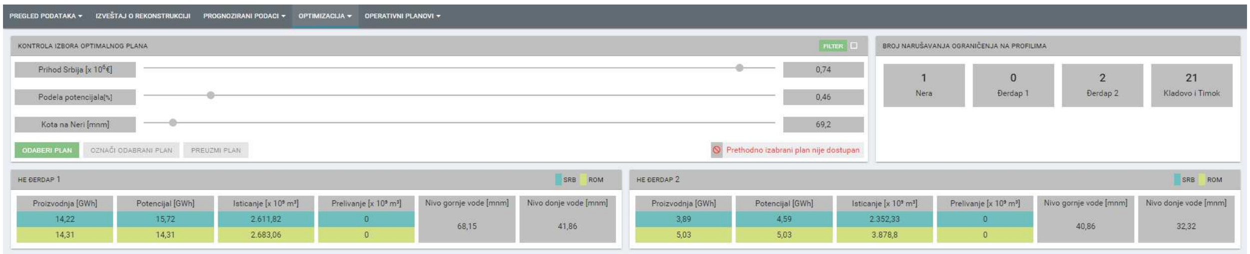

Figure 9. *User interface for selection of production plan from Pareto optimal set*

Moving the slider shown on Figure 9 on any of these scales provides for the user to select one of the plans, where the score of the plan based on that criterion is displayed on the right side of the scale. For example, on the Revenue SRB scale, the user chooses between plans sorted according to the income of the Serbian side, showing on the right how much revenue is expected in case of implementation of the selected plan. Simultaneously with the selection of the plan based on one criterion, the indicators on the other scales are moved to the appropriate position in accordance with the assessment of the fulfillment of these criteria in case of the implementation of the selected plan. In this case, too, the quality of the selected plan is displayed on the right-hand side of each of the scales in terms of the corresponding criteria. The number of the constraints' violations, as well as the overflow volume, if the proposed plan may lead to overflowing, are also reviewed.

The selected plan can be checked by performing a complete computation that provides an overview of all other values, as shown on Figure 10.

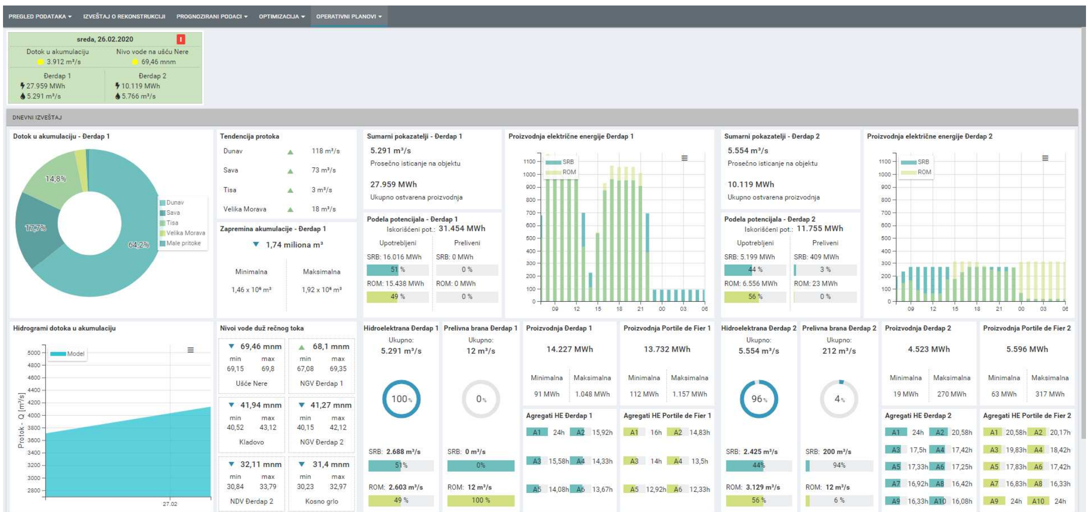

Figure 10. *User interface for overview of selected production plan*

In addition to this tool, planners and dispatchers are in disposal of a user tool for operational support of electricity production and trade in real time. This tool allows checking the system state and adequate planning of the engagement of HPP Iron Gate 1 and 2 in the current power day.

The tool is designed for efficient and automatic updating on hourly basis. The application automatically downloads all the data required for computation that is collected from various systems, without the need to engage users.

Measured levels, power of hydropower units and gate positions on spillways are used as inputs into the computation of the previous period, and the results are reconstructed actual discharge values through the hydropower units, spillway gates and discharge on river courses.

The official production plan provided by Public Enterprise Electric Power Industry of Serbia is used for computation at the level of the current day, which defines the hourly engagement of HPP Iron Gate 1. The plan is automatically downloaded from the location for exchange and an automatic computation done for the period defined by the plan.
In addition to the automatic operation of the tool, the user also has the option to enter a test plan and manually start the computation. This allows dispatchers to reassess the daily production plan at any time and make decisions in accordance with the current situation. It is especially important to note that some situations cannot be analyzed during a daily plan formation (e.g. hydropower unit failures). However, this tool makes it possible to react quickly, without significant deviations from the planned production and without violation of constraints. Figure 11 shows the user tool for operational support to electricity production and trading in real time.

Combination of these two tools in the regular operating conditions allows dispatchers to operate the Iron Gate 1 and Iron Gate 2 hydropower plants with less violation of constraints and better use of the available hydropower potential.

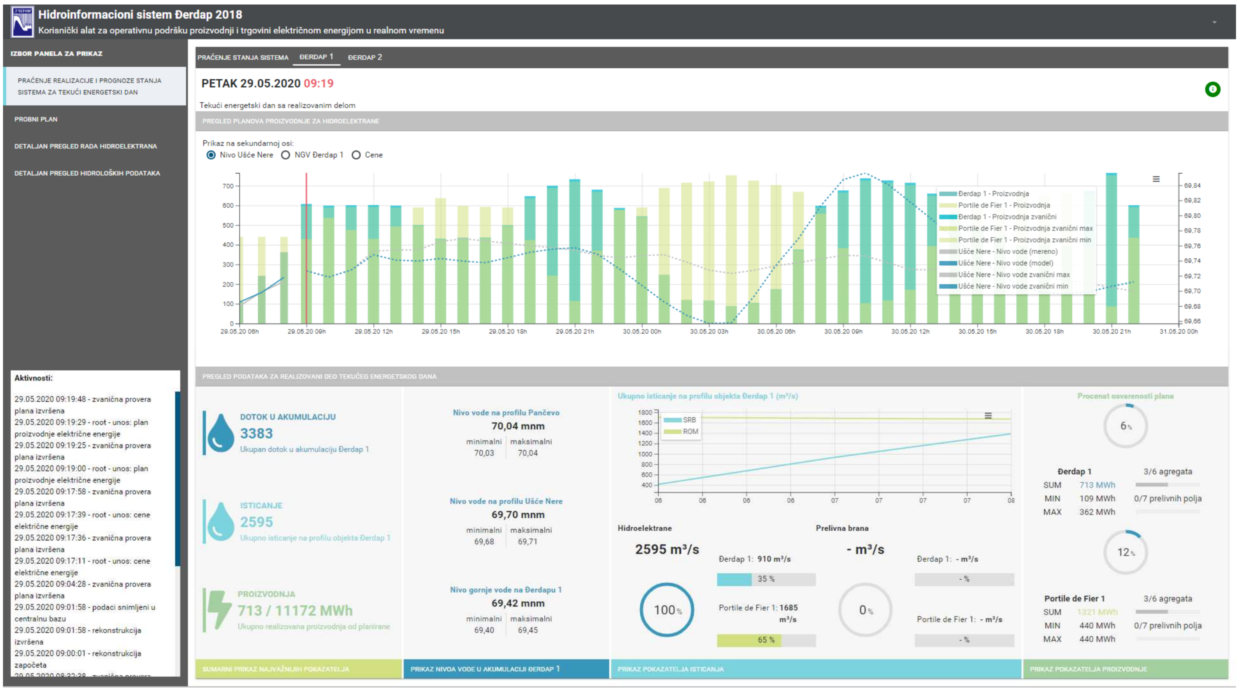

Figure 11. *User interface for real-time tool*

CONCLUSION

In this paper an advanced decision support platform adapted to the requirements and operational constraints of the Iron Gate hydropower system is presented. Proposed platform works with data obtained through existing monitoring system. All required data are acquired, archived and processed by developed data management framework. In this way principle of data integrity is provided which means that whole system works with the same data model. Platform is based on coupled hydraulic-hydropower model designed and calibrated for Iron Gate hydropower system. In order to predict system behaviour in near future as realistic as possible, the model should be updated according to current measurements. It is done by using novel approach proposed in literature based on theory of PID regulation. Updated model started by optimization module a huge number of times generates the same number of possible operational plans enabling decision makers to choose the one that suits them best at the moment. To simplify usage of the model and make decision easier as well, the appropriate software tools within platform have been developed. Those tools cover two important subjects: plan analysis and plan monitoring. The first case considers how each plan affects the operation of the system which results in multi-day optimal plan. The second one considers how previously chosen plan realizes in real-time according to new acquired measurements and forecast.

The proposed platform, although developed and implemented, has potential for further development in domain of the usage of big data concept according to the annually archived data. Mechanism of data quality rating could be improved by involving some artificial intelligence techniques as well as PID adjustments in real-time.

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Editors

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CONTEMPORARY WATER MANAGEMENT: CHALLENGES AND RESEARCH DIRECTIONS

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October 19-20, 2022, Belgrade, Serbia

EDITORS
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PREFACE

Institute of Hydrology was established in 1947 within the Serbian Academy of Sciences. The Hydraulics Laboratory was established that same year within the Federal Ministry of Electricity, a predecessor of the later Hydropower Institute created in 1950. These two institutions were soon merged under the auspices of the Serbian Academy of Sciences into the Hydrotechnical Institute Eng. Jaroslav Černi. This Institute merged with the Serbian Water Management Institute in 1959 to create today's Jaroslav Černi Water Institute.

Over the past decades, the Institute has been the backbone of scientific research in the field of water in Serbia and the former Yugoslavia. The international scientific conference Contemporary Water Management: Challenges and Research Directions is organized to celebrate 75 years of the Institute’s long and successful history. The Scientific Board selected 26 papers to provide readers with the best view of the current research results, as well as the further scientific research directions and potential challenges in the future. Selected papers are classified into six conference topics according to the corresponding research field, although one should note that most of the presented works is multidisciplinary, which is after all a characteristic of a modern problem-solving approach in the field of water. Hence, the chosen conference topics and corresponding papers represent only one possible way of classification of the presented works.

We wish to express our gratitude to the International Scientific Board and the Organizing Committee of this international conference for their efforts in selecting the papers, reviewing, and organizing the conference. We also wish to express our gratitude to all the authors of selected papers for the time they spent presenting the results of their research in a way suitable for this conference, and for contributing to the celebration of 75 years since the establishment of the Jaroslav Černi Water Institute. Respecting the importance of jubilee and wishing to express gratitude to previous generations of scientific workers, the Honorary Committee was also formed.

Following the path of previous generations, the Institute's present and future staff remain privileged, and under duty and obligation to continue and improve the scientific and research work of the Institute in the years and decades to come.

Belgrade, October 2022

Editors

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