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MULTICRITERIA INTERVAL GOAL OPTIMIZATION IN THE REGULATION OF LAKE-RIVER SYSTEMS

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Abstract:

The dynamic multicriteria optimization problem related to the regulation of lake-river systems is a challenging one. It is typical that there are strong control constraints imposed by legislation and the hydrophysics as well as multiple environmental criteria and uncertainties due to weather conditions. We will introduce a dynamic goal programming approach to the multicriteria control problem where the dynamic equations represent the system to be optimized. We will compare the methods of using goal intervals and goal points. The expected benefit from using intervals is that it makes the solution smoother or more robust and increases flexibility in solving the problem without sacrificing the regulation goals too much. By relaxing goal points to goal intervals or by combining the two we hope to find better regulation strategies. We use data related to a lake-river system in Finland to demonstrate the solution.

INTRODUCTION

The use of multicriteria optimization and decision support in the regulation of lake river systems was suggested and tested already in the 1970's. The seminal contributions include [3, 4, 9, 13], for reviews and references see e.g. [1, 10, 11, 14, 15, 16]. In this extensive literature on reservoir optimization the early papers focused on the optimization of the hydraulics under uncertainties. The criteria were usually related to water levels in different weather conditions and times of year.

The explicit consideration of more general economic, environmental and social criteria have been mainly used in decision analytical multicriteria evaluation models where a set of given strategies is compared [1, 5, 7, 11]. In these approaches the interactive use of the evaluation models by the stakeholders is essential. Interactive decision analysis is possible because the related computations are easy. However, in multicriteria optimization with the dynamics of the lake river systems included, the computational issues become challenging and the related interactive decision support systems become quite challenging.

In our project (for details see www.paijanne.hut.fi) we developed a software running a dynamic goal programming model called ISMO [5]. It was used interactively with the stakeholders so that they could specify their goals and evaluate the impacts of the resulting regulation strategies. In this paper we use the same basic model but focus on the different goal programming formulations. In particular we discuss the use of intervals in specifying the goals. This new approach also allows to embed different stakeholder goals into the same model so that the interval is defined by the extreme opinions. Moreover, in a dynamic setting where the hydraulics are essential it may be better to use intervals rather than point values as goals as they leave room for flexibility in the solution. The current paper describes results related to the development of a new multicriteria regulation policy which takes into account a wider set of objectives [7, 8].

THE LAKE-RIVER SYSTEM AND DYNAMICS OF THE LAKE

This paper is based on a project related to the regulation strategies of the Päijänne-Kymijoki lake-river-system in Finland. Lake Päijänne is 120 km long and 20 km wide. Its water level varies between 77.5-79 meters above the sea level and it discharges through several smaller lakes into River Kymijoki which is 200 km long and flows into the Gulf of Finland.

The system has an extensive number of stakeholders. There are twelve hydropower plants along the River Kymijoki with a total capacity of 200MW (9 % of hydropower capacity in Finland). About 350 000 people live around this lake-river system. Fishing, recreation, transportation and agriculture are among the important activities affected by the regulation. The watershed is also important for bird life. The regulation was originally initiated in

1964 to reduce flooding during spring and to enhance hydropower production.

In our model the lake dynamics is approximated by using a simple model. Water level x_i in the lake is assumed to depend dynamically on the net inflow and the surface area of the lake. The net inflow is the difference between average inflow q_i^{in} and average discharge q_i

$$\Delta q_i = q_i^{in} - q_i. \tag{1}$$

The discharge consists of the regulated outflow through the dam and the natural outflow through the rapids of Kalkkinen in the side stream.

The surface area of lake Päijänne has been approximated with historical data by a piecewise linear function $A(x) = \alpha(x)x + \beta(x)$. The difference in the water level can be calculated by solving the relation

$$\Delta q_i \Delta t_i = \int_{x_{i-1}}^{x_i} A(x)dx \tag{2}$$

for $\Delta x_i = x_i - x_{i-1}$ using numerical integration. However, in our spreadsheet model the change in the water level has been approximated in two phases by

$$\tilde{x}_i = \tilde{x}_{i-1} + \frac{\Delta q_i \Delta t_i}{A(\tilde{x}_{i-1})} \tag{3}$$

$$x_i = x_{i-1} + \frac{\Delta q_i \Delta t_i}{A(\frac{x_{i-1}+\tilde{x}_i}{2})}. \tag{4}$$

The initial condition $\tilde{x}_0 = x_0$ is taken from historical data. In this approximation the $\tilde{x}_i$ sequence is independent of the actual water level sequence x_i. This means that with an initial water level and inflow the new water level depends on the sequence history, i.e. on the value of $\tilde{x}_i$, which may or may not be close to the actual water level x_i. This method gives sufficiently accurate results with lake Päijänne.

The natural outflow through the rapids of Kalkkinen is estimated by a piecewise linear function of the water level. The legislated hard constraints of the system include the minimum (120 m^3/s) and maximum (500 m^3/s) bounds for total outflow of Lake Päijänne and maximum rate of change in the outflow (50 m^3/s / 5d) which are imposed by legislation.

MULTICRITERIA REGULATION OF THE LAKE-RIVER SYSTEM

The inflow into Lake Päijänne varies a lot both seasonally and from one year to another. The regulation constitutes a dynamic multiobjective optimization problem. *Multiattribute decision analysis* and *multiobjective optimisation* follow different approaches. In multiattribute decision analysis the set of feasible solutions is evaluated and they are predetermined and finite. In multiobjective optimisation we look for the set of efficient alternatives subject to multiple criteria. In this paper we will concentrate on the multiobjective optimisation problem, generally defined in the form

$$\text{minimise} \quad \{f_1(\boldsymbol{x}), f_2(\boldsymbol{x}), ..., f_k(\boldsymbol{x})\} \quad \text{subject to } \boldsymbol{x} \in S,$$

where we have k ($\geq$ 2) objective functions $f_i : \mathbb{R}^n \rightarrow \mathbb{R}$. The vector of objective functions may be denoted by $\boldsymbol{f(x)} = (f_1(\boldsymbol{x}), f_2(\boldsymbol{x}), ..., f_k(\boldsymbol{x}))^T$. The decision variable $\boldsymbol{x} = (x_1, x_2, ..., x_n)$ belongs to the nonempty feasible set S.

Our problem includes strong control constraints imposed by legislation and the physical environment as well as important uncertainties in the form of weather conditions. We will use a dynamic goal programming approach to the multicriteria control problem where the dynamic equations represent the system to be controlled. We will compare the methods of using goal sets or *intervals* instead of and together with goal points. The idea in using intervals is assumption that it would make the solution smoother or more robust and increase the flexibility in solving the problem.

The optimisation procedure follows the one used in the regulation practice. It includes using six goal points and/or intervals annually over a period of one to five years (Figure 1). The model is discretised using periods of 10 days. Because of the historical inflow data, it is convenient to consider every 1^{st}, 11^{th} and 21^{st} day of each month which implies that the time intervals are not of exactly equal lengths. The forecasts are given once a month over a period of one year but, since it would make no sense to use forecasts one year ahead, the decisions are made using a rolling two-goal point planning horizon. Solving the problem for the active planning period is iterated after each new forecast.

A spreadsheet application ISMO [5] was used for handling the initial data, optimising as well as for visualising the results. The solver of Excel was used and the spreadsheet offers a wide range of graphics and statistics to present the results.

DYNAMIC GOAL PROGRAMMING USING INTERVALS

The ideas of goal programming were originally introduced already in 1955 by Charnes and Cooper [2]. It is one of the first methods expressly created for multiobjective optimisation. The basic idea in goal programming is that the decision maker specifies desired goal levels for the objective functions and the actual optimization problem uses the deviations from the goals as the objective function. A goal can be considered as a *flexible* constraint. Goals are of the form $f_i(\boldsymbol{x}) \leq z_i$ where z_i stands for the aspiration level of the objective function to be minimised. The aspiration levels are normally assumed chosen so that all of them are not achievable simultaneously.

After fixing the flexible (goals) and inflexible constraints the objective function is formed to minimise the deviations from the goals. It suffices to study the deviational variables $d_i =$

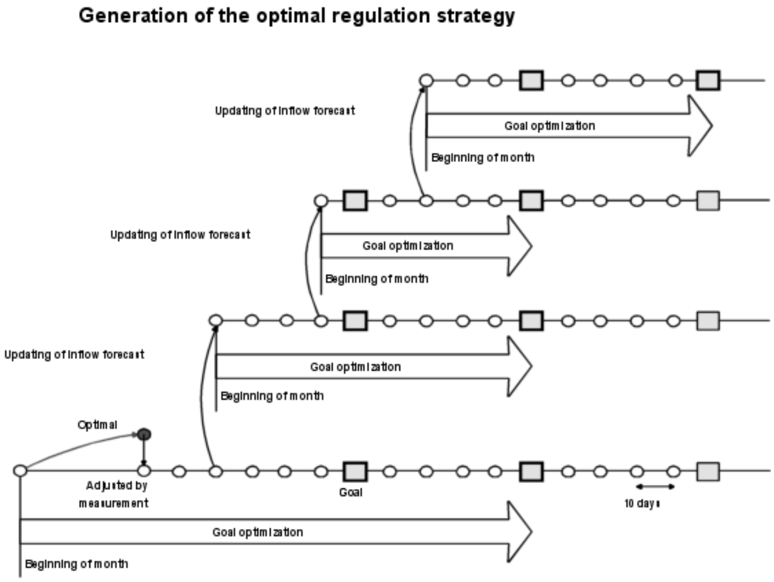

Figure 1: Generation of the regulation strategy

$z_i - f_i(\boldsymbol{x})$. The deviational variable may take positive or negative values so it is convenient to present it as the difference of two positive variables, that is, $d_i = d_i^- - d_i^+$, $(d_i^-, d_i^+ \geq 0)$, where d_i^- is a *negative deviation* or *underachievement* and d_i^+ is *positive deviation* or *overachievement* relative to the aspiration level. The solution depends on the weighting of different goals. It is usually done by applying weights summing up to one ($\Sigma w_i = 1$).

$$\min \Sigma_{i=1}^{k} w_i(d_i^- + d_i^+) \quad (5)$$
$$\text{subject to}\, f_i(\boldsymbol{x}) + d_i^- + d_i^+ = z_i,$$

Interval goal programming is our extension [3, 4] to the model so that the goal is defined as an interval of points rather than a single point. The idea is to find the closest solution to the goal set.

The strategies are defined using six annual goal points as the ideal water level of lake Päijänne with lower and upper acceptability bounds for each point. We use dynamic interval goal programming to optimise the system. Thus, the problem becomes one of minimising the deviations from these goals for given inflow data over the planning period.

The deviations from the goal point and from the interval may be weighted independently.

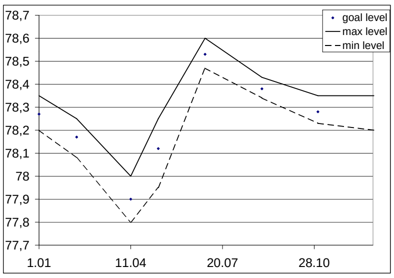

Figure 2: The goal intervals used in the simulations

We use a penalty function with quadratic deviations:

$$F(x_k, \Delta q_i) = c_g \sum_{k=1}^{K} f_k + c_i \max((x_k^{min} - x_k)^2, (x_k - x_k^{max})^2, 0) + \qquad (6)$$

$$c_q \sum_{i=1}^{N} \max\big(\big(|\Delta q_i| - \Delta q_{max}\big), 0)^2 + c_r |\Delta q_i|,$$

$$\text{where} \quad f_k = (x_k^{goal} - x_k)^2, \quad \Delta q_i = q_i - q_{i-1}$$

and k refers to the goal points during the optimisation period. The goal water levels x_k^{goal} are set by the regulator for the six annual control dates. The second to last term is the soft constraint for the maximum change in the flow rate and the last term is an outflow rigidity term that penalises changes in the outflow rate.

The objectives of the regulation are diverse. Different interest groups have different preferences for the water level at given times of the year. For example the fishermen wish to protect the reproduction of fish with a high and stable water level during the spring. The objective of the power companies is to maximize profit, i.e. to maximize the flow especially during winter when electricity price is high which results in strong variations in the water levels. Farmers would like to keep the water level sufficiently low to ensure the avoidance of flooding. We have estimated the dependence of the above attributes on the water levels at different times of the year.

RESULTS AND COMPARISON

When solving for the real regulation years have been divided in three categories - wet, normal or dry - following the average amount of precipitation, and different goal sets have been defined for them. Our analyses here have been made using the set of goal points recommended by the Finnish Environmental Institute and perfect forecasts for the inflow. In the real project also the effects of uncertain forecasts were studied.

The regulation strategy is determined by the penalty function parameters and the goal points and intervals. We compare different parameter and goal settings. The parameters are marked in the legend of the figures as (c_g, c_i, c_q, c_r).

The penalty function (6) of the dynamic goal programming problem plays an important role in achieving the desirable solutions. We experimented with different weight parameters to produce better solutions with the interval strategy. The penalty function is visualised in figure 3.

Figure 4 shows a comparison of three different strategies during the years 1990-1994 using parameters with a high penalty term compared to outflow rigidity ($c_g = 0, c_i = 1000, c_q = 1, c_r = 1$). In figure 5 the same years are used for comparison of strategies with smaller outflow rigidity parameters $c_g = 40, c_i = 100, c_q = 1, c_r = 0.1$.

The strategy with a higher outflow rigidity parameter (figure 4) is smoother and the interval strategy smoothens the outflow curve even further. The combination strategy curve lies nearly always between the goal point and interval strategy curves. The interval strategy lets the water level rise too high in the first spring when smaller penalty parameters were used. The solution with higher penalty function parameters performs better.

We also compared the solutions with respect to the other criteria including pike spawning and loon nesting as well as hydropower.The interval strategy is slightly more favourable considering these impacts. This is probably due to the more stable outflow and water level when using interval strategy. One exception is loons' nesting in 1981 where the soared water level with interval strategy regulation is bad for the nests.

CONCLUSIONS

We studied the advantages of using goal sets instead of strict goal points in designing a multicriteria regulation policy and compared the effects of different formulations.

In deriving the overall strategy one has to find suitable penalty function coefficients as well

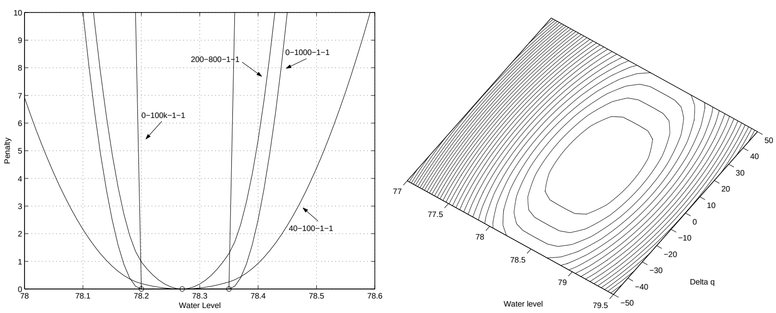

Figure 3: The penalty function (left) with different parameters and a contour plot (right) with c_g=40,c_i=1000,c_r=1

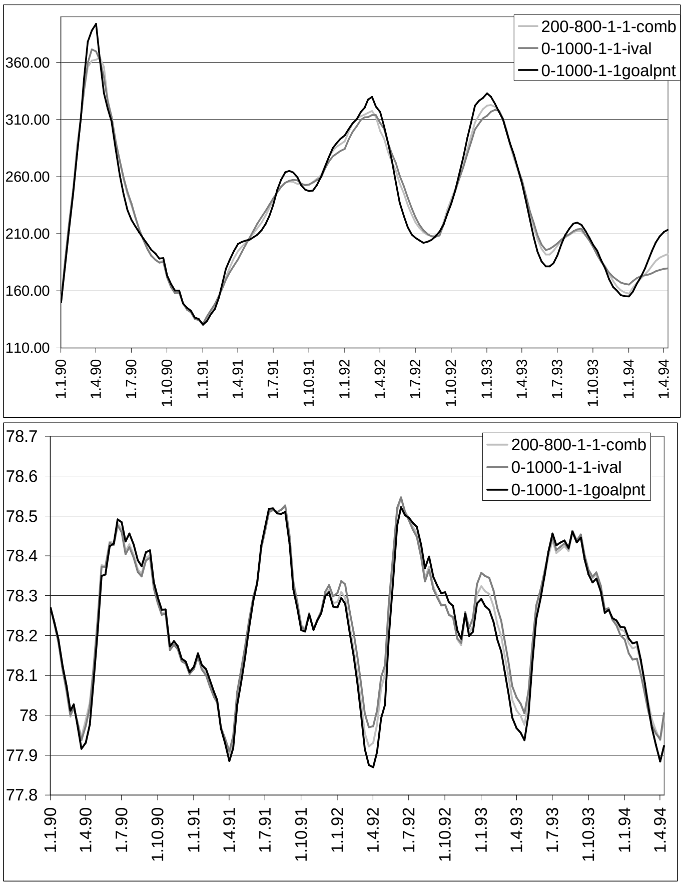

Figure 4: Regulation results for 1990-1994 outflows and water levels for different strategies with a high outflow rigidity parameter

as to define the goal points and sets. The penalty function's role is at least as important in the formulation as the goal settings. By choosing right the relative weights of penalising deviations from goal points and intervals and changes in the outflow, we were able to generate solutions that sufficiently satisfy the conflicting needs of smooth outflow regulation without sacrificing too much the water level goals.

The interval approach resulted in smoother outflow at the expense of being more likely to violate the water level targets. The interval strategy could lead to flooding as the water level may be high already in the beginning of a wet period. The interval strategy takes advantage of the goal bounds to avoid unnecessary changes in the outflow. However, it occasionally let the water level go out of the goal range. The combined strategy ran somewhere between the goal point and interval strategy. The use of goal intervals clearly adds a new element in the design of a multicriteria regulation policy.

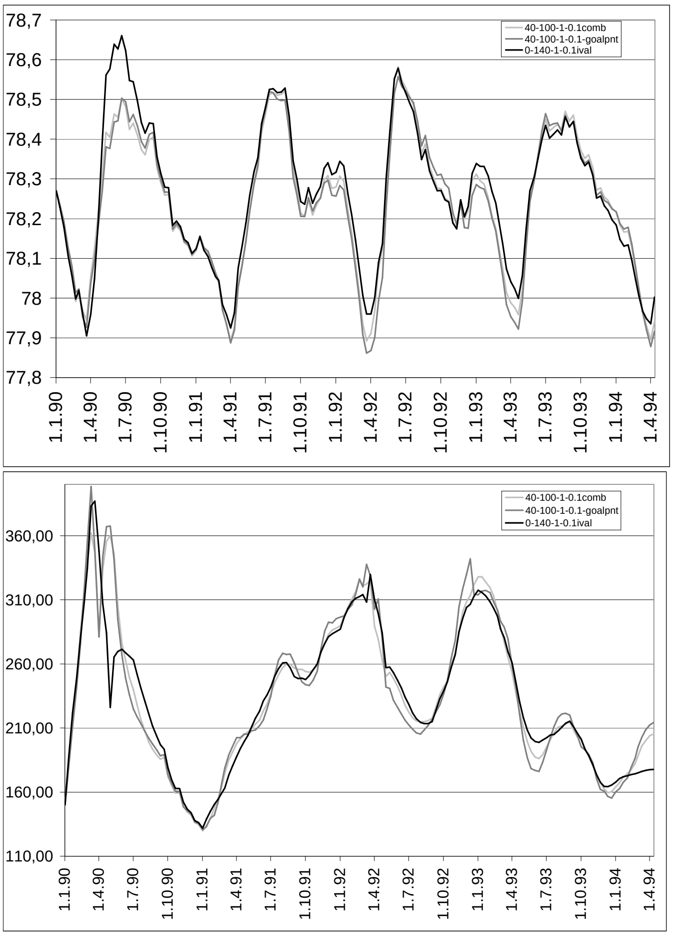

Figure 5: 1990-1994 outflows and water levels with different strategies with a small outflow rigidity parameter - interval strategy lets the water level go too high

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