Multiple criteria fuzzy supported on-line optimization for process control

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ABSTRACT: The contribution includes a presentation from a concept for optimal control from non-linear technical and non-technical systems. A procedure for multiple criteria fuzzy-supported on-line optimization of controlling trajectories is shown. In this case, the weighting factors for the partial criteria of a total goal function are determined time and situation related by a fuzzy system. The effectiveness of this procedure is shown at the example of the coordinated control of hydropower stations at Austrian Danube.

KEYWORDS: fuzzy supported optimization, multiple criteria optimization, non-linear systems, coordinated control, hydropower stations.

1 INTRODUCTION

A method for multiple criteria fuzzy supported on-line optimization is presented in this contribution. In the case of technical and nontechnical processes, the task often consists in the determination of an optimal control trajectory. That leads to an optimization problem in many cases of application. For these cases, many solutions already exist in specialist literature [1, 2]. The transformation into a scalar problem is used here. So the total goal value consists of the weighted sum of the partial goal values. It is valid

$$I_{total} = \sum_{i=1}^{n} a_i \cdot I_i . \tag{1}$$

The problem during the formulation of the total goal function consists in choice of the weighting factors α_i. In the case of many processes, these weighting factors are dependent on the time and/or the process situation [3, 4, 5]. Consequently, the following relationship is valid.

$$a_i = f(time,\ situation)\ . \tag{2}$$

In this contribution, a Fuzzy system is presented which determines the weighting factors α_i in dependence on the process situation. As a result, the control trajectory can be computed by application of an optimization algorithm. The optimization is formed repeatingly to adapted the control trajecory to current process situation. Finally, the effectiveness of this procedure is shown at the example of computation of the optimal discharge trajectory for coordinated control of two Danube reservoirs Melk and Ybbs.

2 METHOD FOR MULTIPLE CRITERIA FUZZY-SUPPORTED ON-LINE OPTIMIZATION (MEFURO)

As mentioned already in the most cases of technical or nontechnical processes the computation of optimal control trajectories leads to a multiple criteria dynamic optimization problem. This problem can be transformed to a scalar goal function in accordance with equation 1. For temporal reasons a manual determination of the weighting factors α_i is rarely possible with automatic systems. In addition, the quality of control with this method is dependent on the competence of user. For these reasons it was necessary to develop a system which makes possible an autonomous determination of the weighting factors in dependence on the process situation. In this way, the preconditions for an repeating optimization are met at the same time. For instance, at a time of k determined control trajectory becomes invalid at the time of k+1, because process situation is changed. Therefore it must be computed again with varied weighting factors. A novel solution for this problem was developed with the MEFURO-concept. For the first time a Fuzzy system is used for weighting factors computation of partial goal criteria. In figure 1, the principle of the MEFURO concept is shown.

A model of the process must be available for the determination of the control trajectory with the MEFURO concept. Starting from the manipulated variable matrix U, the output matrix Y and the state matrix X are computed. In the fuzzy system, the weighting factors α_i are computed for every partial criterion and delivered to the module as a vector for determination of total goal function. These vectors contain each one value per time step. The weighted sum of the partial criteria is computed here for every time step. A goal value is determined by integration over the considered period. This value is delivered an optimization algorithm. The described procedure is so often repeated until a termination criterion is achieved. In this way, the optimal control trajectory was found [3].

The process situation can change through disturbance signals. As a result, it is required to carry out the calculation of the control trajectory repeatingly. In this way, an adaptation is possible for the control trajectory starting from the current situation. The time periods for it are dependent on the concrete case of application. Simplex procedure and evolution strategies proved effective for the solution of these multiple criteria dynamic optimization problems. The structure of the fuzzy system is dependent on the case of application. It is explained in the following example.

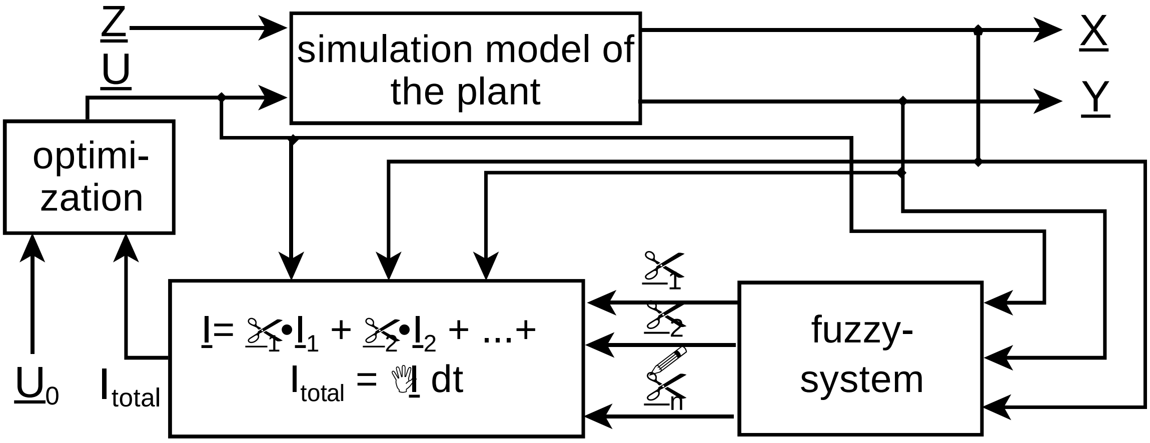

Figure 1 Principle of the multiple criteria fuzzy-supported on-line optimization

3 APPLICATION OF THE MEFURO CONCEPT TO COORDINATED CONTROL OF DANUBE RESERVOIRS

At the example of the Austrian Danube reservoir cascade Ybbs-Persenbeug/Melk ,the new concept is presented. Figure 2 shows this cascade.

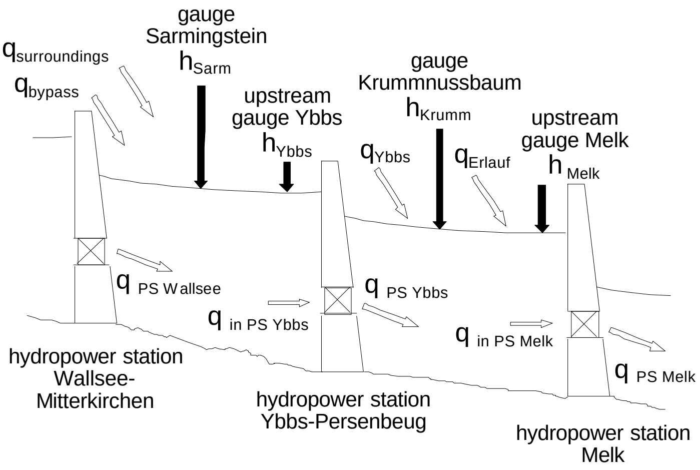

Figure 2 System of Danube reservoir cascade

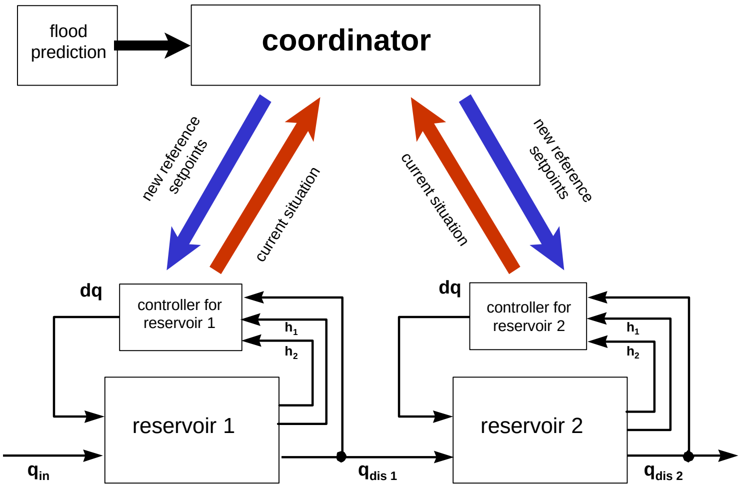

Figure 3 Principle of coordinated control

The length of the reservoir Melk is 22,5 km. There are three important flows into this reservoir, the discharge of hydropower station Ybbs-Persenbeug and the two tributaries Ybbs and Erlauf. Two gauges are important for the control strategies. These are the upstream gauge near the barrier and the gauge Krummnussbaum in the middle of the backwater area. The distance between this gauge and the upstream gauge Melk is about 10 km.
Reservoir Ybbs-Persenbeug is built up similarly. Differences are absence from tributaries and existence from retention rooms. In the case of a flood, that leads to an extreme non-linear behavior. This reservoir extends over a length of 34 km.

The previous control concepts do not solve the multiple criteria process management problem of reservoir casacdes satisfactorily [4, 6 -8]. Therefore, a concept was developed which allows a forecast aided coordinated optimal control. In figure 3 the principle of this concept is shown. The change from normal water situation to flood situation and the flood situation itself are from special importance.
The aims are:

- energy optimal change from control in normal water situations to control in flood situations,
- maximally possible flow peak reduction of the flood and
- guarantee of navigation, prevention of limiting value violations, e.g. rate of water level changes.

Thus weighting factors of partial criteria in the total criterion are strong situation related. Starting from a flow forecast, a control trajectory is computed for every hydropower station in the cascade. Flow forecasts, especially in the flood case, are only possible for a short time horizon. Therefore, the computation of the optimal control trajectories is carried out repeatingly. After updating forecast, an optimization is started in consideration of the varied situation. The goal function can be formulated as follows in accordance with the mentioned demands and in consideration of constraints G_1 and G_2:

$$I(t) = a_1(t)\cdot I_1(t) + a_2(t)\cdot I_2(t) + a_3(t)\cdot I_3(t) + a_4(t)\cdot I_4(t)\ . \tag{3}$$

In table 1, the partial criteria and the constraints are explained.

criterion	meaning
$I_1(t) = q_{dis,max}$	The maximum discharge of the chain of power stations is minimized.
$I_2(t) = \left(\frac{dq_{\text{dis}}(t)}{dt} \right)^2$	A steady discharge in the range of flow peak is forced.
$I_3(t) = \int (h_{\text{backwater}}(t) - h_{\text{set point}})^2 dt$	The set point must be achieved at the end of a flood.
$I_4(t) = -\int P(t)\, dt$	The generated electric energy is maximized.
$G_1(t) = \left(h(t) - h_{\max} \right) \leq 0$	The water level at a defined gauge must not exceed a peak value.
$G_2(t) = \left(\frac{dh(t)}{dt} - v_{\max} \right) \leq 0$	The rate of water level change must not exceed a peak value.

1. Partial goal functions and constraints for reservoir cascades

The basic construction of a system for computation of the weighting factors of partial goal functions is represented in Figure 4.

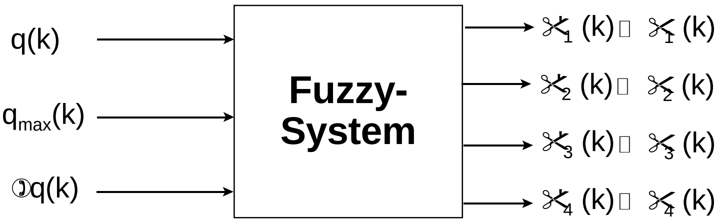

Figure 4 Fuzzy system for computation of weighting factors

For every sample time, it is possible to determine the corresponding values of the individual weighting factors $\alpha_1(k)$, $\alpha_2(k)$, $\alpha_3(k)$ and $\alpha_4(k)$. For this purpose, the following information must be available:

- the current incoming flow q(k) into the reservoir,
- the expected flow maximum $q_{max}(k)$ from the current time seen and
- the predicted ascent of the flow $\Delta q(k)$.

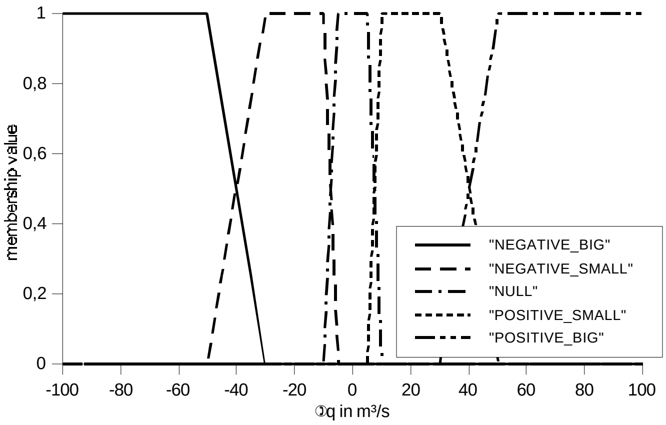

Figure 5 Membership functions for flow gradient Δq.

Output variables of the system are first the weighting factors $\alpha_1'(k)$, $\alpha_2'(k)$, $\alpha_3'(k)$ and $\alpha_4'(k)$. For the use as weighting factors in the goal function, it is reasonable to standardize these factors. In such a way, the standardization occurs that the sum at every time yields one. The membership functions for the input variables were determined trapezium shaped. Singletons with the terms „low“, „middle“ and „high“ are used for the output variables. Figure 5 shows the membership functions for flow gradient Δq [9, 10].

All situations which are relevant for choice of the weighting factors must be considered during the development of the rule base. They are:

situation 1:	normal water situation
situation 2:	change from normal water situation to flood situation
situation 3:	flood situation
situation 4:	change from flood situation to normal water situation.

A rule base was projected for every situation. As a example, the rules for situation 1 are shown in table 2.

R1: if(q(k) =LOW) and (q$_{max}$(k) =LOW) then á$_4$ (k):=HIGH
R2: if (q(k) =LOW) and (q$_{max}$(k) =LOW) then á$_3$ (k):=HIGH
R3: if (q(k) =LOW) and (q$_{max}$(k) =LOW) then á$_2$ (k):=LOW
R4: if (q(k) =LOW) and (q$_{max}$(k) =LOW) then á$_1$ (k):=LOW

2. Rule base for normal water situation

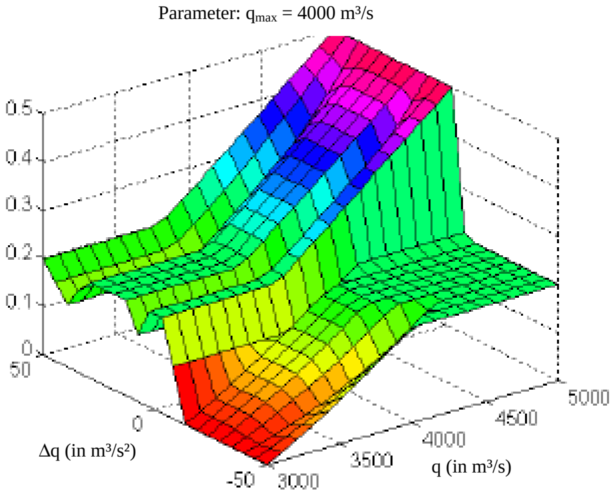

Figure 6 Weighting factor α_2 as a function of q and Δq

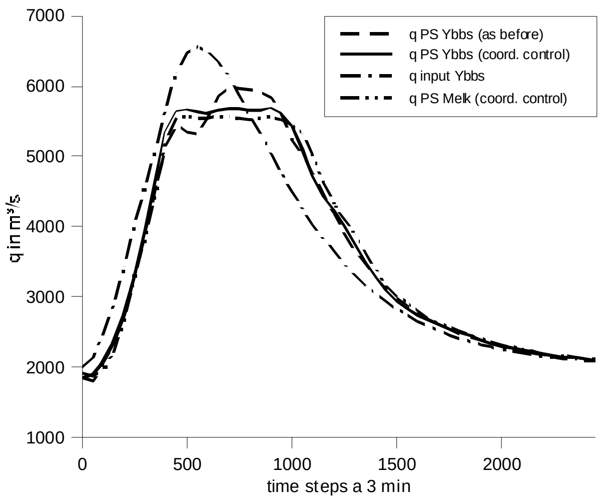

Figure 7 Flow trajectories of hydropower stations Ybbs-Persenbeug and Melk

For this situation, the predicted gradient $\Delta q(k)$ is unimportant and therefore, is not used in the rule base. If the flow into the reservoir cascade is „LOW“ and the predicted peak value also is „LOW“ then α_3 and α_4 are „HIGH“. While α_1 and α_2 is „LOW“. It means, that the two criteria for adherence of upstream gauge setpoint and maximizing of generated energy are highest weighted. On the other hand, the other criteria for flood control have no importance.

For the better illustration, the weighting factor α_2 is represented in figure 6 as a function of flow and gradient of flow. The predicted maximal flow is used as parameter and has a value from 4000 m^3/s. The results of coordinated control for the reservoirs Ybbs-Persenbeug and Melk are shown at the example of a flood with a peak flow of approx. 6500 m^3/s. That for instance corresponds to a 10-annual flood in this field of Danube. Further investigations for other flow ranges and robustness compared to forecast inaccuracies are presented in [3]. The flow trajectories are represented in Figure 7. The flow difference between the incoming flow in Ybbs-Persenbeug and the flow which results in the case of control with the previous operating regime, correspond to the peak flow reduction by retention rooms. With the previous control regime, the flow is passed on without significant influencing.

The discharge behaves differently in the case of coordinated control [7]. A plateau with a flow of about 5700 m^3/s is to be recognized clearly. It covers a period of 26,5 hours. In this way, it succeeded to reduce the peak flow by 320 m^3/s. One considers the effect of the retention room, the reduction is 890 m^3/s. The balance of electric work shows a surplus from 165 MWh for the coordinated procedure. This corresponds to 1% of generated electric work during this flood. Thus is achieved in addition to better flood control also a surplus during energy production with coordinated control.

It can be found summarizingly that a reduction of the peak flow is possible in every flow range with the new MEFURO-concept for coordinated control unlike the previous control regime. However, with increasing peak flow, the achieved effect is less. The cause for it is, that the free storage volume within the reservoirs is reduced with increasing flow. In this way, the limits of coordinated control are clear. In cases of extreme floods, no significant improvement in flood control can be achieved by coordinated control. It results the following conclusion. A coordinated control can complete useful flood control with available retention rooms, however, never replace this [11].

4 OUTLOOK

Now the practical conversion of the new multiple criteria fuzzy-supported on-line optimization concept (MEFURO) into process control of the hydropower plants begins after the development and the test by simulation. For this purpose, a completely new process control which a central control allows must be install in the power stations. This concept is already in off-line use in four hydropower stations as a C-program. They are supplied on-line with data but do not control the hydropower stations. The aim is the inclusion of all nine power stations into coordinated control. At present the simulation models and control strategies for the remaining hydropower stations are developed.

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