DECISION SUPPORT MODEL SYSTEM FOR THE ANALYSIS OF REGIONAL WATER POLICIES IN AN OPEN-PIT LIGNITE MINING AREA OF THE GDR

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ABSTRACT

A decision support model system for the analysis of regional water policies in open-pit lignite mining areas has been developed in competence of the International Institute for Applied Systems Analysis. It is verified and implemented for a test region in the Lusatian Lignite District of the German Democratic Republic. The paper describes one of its major components – a planning model for multi-criteria analysis. The underlying mathematical model is outlined for the test area, depicting examples of its major sub-models as indicators of systems development. Finally the solution procedure, the structure of the model system, and its practical application are explained.

INTRODUCTION

Generally regions with open-pit lignite mining are characterized both by significant impacts on the environment and consequently by conflicting interests of the mining industry, different water users, agriculture, and of environmental protection authorities.

A detailed analysis of the problems related to water management due to lignite mining is given by Kaden et al. (1985a,b). In order to emphasize the scale of those problems for the German Democratic Republic (GDR) only a few numbers will be repeated.

More than two-thirds of the total output of primary energy of the GDR is based on lignite extracted exclusively by open-pit mining. The annual output of lignite will amount to 300 million tons in 1985. Thereby, it is necessary to pump out 1.7 billion m^3/annum water for dewatering of the open-pit mines. Bearing in mind the stable runoff (surface runoff) of the GDR of 9 billion m^3/annum – the amount of mine water is about 20% of the stable runoff of the whole country.

Due to the complexity of the socio-economic environmental processes in mining areas, the designing of water management strategies and water use technologies as well as mine drainage can only be done properly based on appropriate mathematical models. These models should serve as tools to match the criteria of the interest groups and to reconcile conflicting interests. The state-of-the-art of water resources modelling for open-pit lignite mining areas, being analyzed by Kaden et al. (1985b), reveals the apparent need for the *development of methods and models for the analysis of long-term policies* to reconcile those conflicting interests. The development of a policy-oriented decision support model system for such analysis, and its implementation for a test region in the GDR is part of the research work in the Regional Water Policies project carried out at the International Institute for Applied Systems Analysis (IIASA) in collaboration with research institutes in the GDR and in Poland.

The principal methodological approach for the DSMS has been substantiated and explained in Kaden et al. (1985a,b). To summarize, taking into account the policy-making reality related to long-term regional water management and planning two different step-sizes discretizing the *planning horizon* T (of about 50 years) are considered:

- the *planning periods* between 1 and 15 years as the time step for principal management/technological decisions (e.g. water allocation from mines, water treatment, drainage technology)

- the *management periods* of one month for management decisions within the year related to short-term criteria as the satisfaction of monthly water demand (the classical criteria for long-term water resources planning).

Consequently, the model system consists of two major components:

- *planning model* for dynamic multi-criteria analysis for all planning periods in the planning horizon

- *management model* for the stochastic simulation of monthly systems behaviour in the planning horizon.

In the following the first model component – the *planning model* – will be demonstrated in more details because it should be of fundamental interest for both major interest groups, the mining industry as well as the water users. The *management model* is similar to typical models for long-term water management in catchment areas.

MATHEMATICAL MODEL FOR THE GDR TEST AREA

Overview

A detailed description of the test area in the Lusatian Lignite District, see Figure 1 for a schematic overview, has been given by Kaden et al. (1985a,b). We consider a planning horizon of 50 years, divided into 10 planning periods as depicted in Table 1.

Table 1: Time discretization of the planning model for the GDR Test-Area

j	1	2	3	4	5	6	7	8	9	10
Planning period	1981	1982	1983 -1984	1985 -1986	1987 -1988	1989 -1990	1991 -1997	1998 -2005	2006 -2015	2016 -2030
ΔT_j [years]	1	1	2	2	2	2	7	8	10	15
i_B	1	2	3	5	7	9	11	18	26	36
i_E	1	2	4	6	8	10	17	25	35	50

i_B - first year per period; i_E - last year per period.

For the development of the model for multi-criteria analysis the following groups of submodels are distinguished:

- *Indicators* of systems development (socio-economic and environmental indicators) to be considered as criteria or constraints for the analysis (see below),

- *Descriptors* of systems development characterizing the state of the water resources system,

- *Constraints* on systems development.

In Figure 1 a scheme of the test region is given, depicting the essential *decisions* on the systems development and *descriptors* of the systems development. The following *decisions* on systems development (the used indices are given in Figure 1) are taken into account:

$\mathbf{q}_{\alpha,\beta}$ - flux from α to β (water allocation)
α = (a|b|c|d|s|g|p|im|i), β = (s|m|i|ag|ex|p|e)
$\mathbf{cq}_{\alpha}$ - supply of lime hydrate for water treatment, α = (a|b|c|d|p)
$\mathbf{\Delta tm_d}$ - duration of mine drainage mine D before starting its operation
$\mathbf{maxh}_p$ - maximum water level in the remaining pit

The present model considers only continuous decision variables. Discrete decisions on investment, for instance, to construct a treatment plant, an allocation pipe have to be done in a preparatory stage. In the long-term planning model bounds for the decision variables are considered, reflecting these investment decisions, e.g. the maximum flow through a pipeline according to its diameter.

As *descriptors* of the systems development we consider:

$\mathbf{qg}_{\alpha}$ - groundwater flow to α, α = (a|b1|b2|c|d|p)
$\mathbf{qi}_{\alpha,\beta}$ - infiltration balance segment $\Delta s_{\alpha,\beta}$
h_{α} - representative groundwater table, α = (ag|g|e)
$cg_{\alpha}(l)$ - concentration of component l in the flow to α, α = (a|b1|b2|c|d|p)
$l=1 \rightarrow Fe^{2+}$, $l=2 \rightarrow H^{+}$
$c_{\alpha}(l)$ - concentration of component l in drainage water after treatment
qs_{α}, hs_{α} - flux, respectively surface water table at the balance profile bp_{α}.
$cs_{\alpha}(l)$ - concentration of component l in the flux through balance profile bp_{α}
$q_{i,s}$ - quantity of industrial waste water
$c_{i,s}(l)$ - concentration of component l in the industrial waste water
$\mathbf{h}_p$ - water table in the remaining pit
$c_p(l)$ - concentration of component l in the remaining pit
v_p - storage volume in the remaining pit.

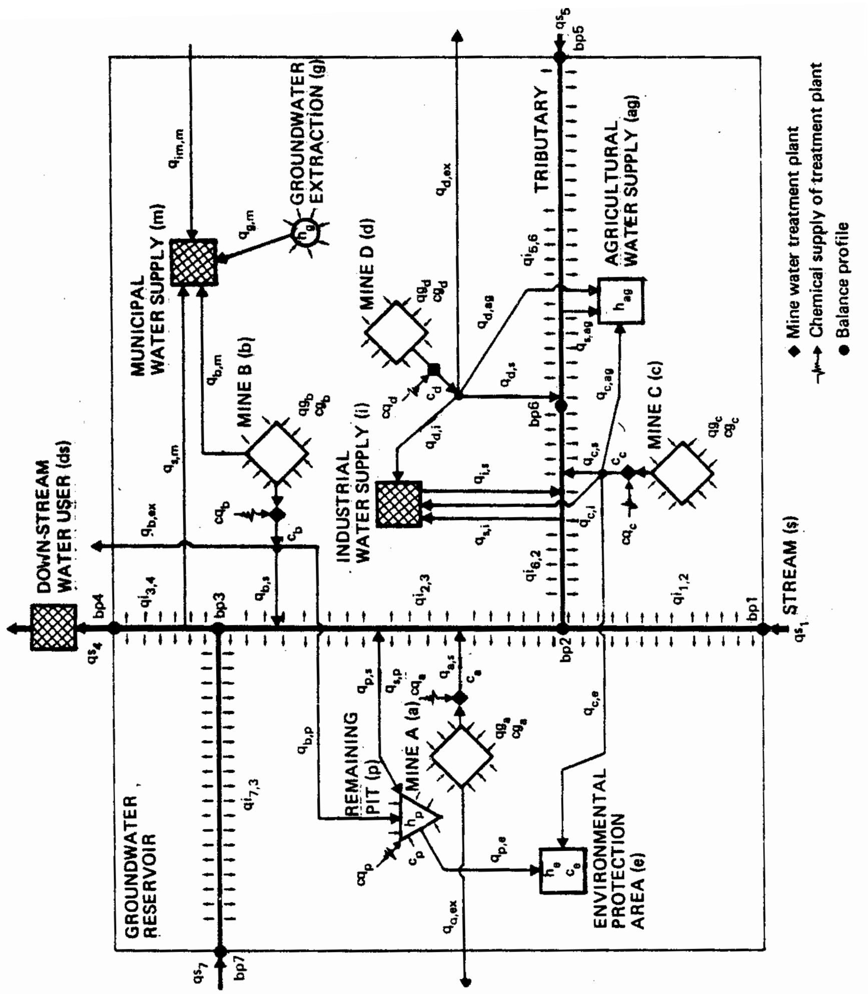

Figure 1: Detailed scheme of the test region.

We use as notation of time dependency for the mean value of x for period j $x(j)$. Mine drainage of mine A is terminated in the planning period $j_a = 7$, after this period the remaining pit has to be considered. The mine drainage of mine D can start in period $j_d = 3$.

Indicators of Systems Development

We consider three types of indicators

- *deviation between water demand and supply* measured in m^3/s as the mean value for a given time unit,

- *environmental quality* for typical water quality parameters (Fe^{2+}, H^+) measured in g/m^3 as the mean value for a given time unit,

- *economic characteristics* of regulating activities.

Water Demand-Water Supply Deviation

From the point of view of water management the satisfaction of the water demand of different users in the region (municipality, industry, agriculture, environmental protection and downstream users) is the most important indicator. For the municipal and industrial water demand we use deterministic trend models for the planning model. In opposition to that the agricultural water demand and the water demand for environmental protection (artificial groundwater recharge) depend on the actual systems state. This will be explained for the agricultural water demand.

In the test area we take into account agricultural water demand for irrigation only. This demand depends primarily on the groundwater tables in the agricultural area and on the actual precipitation. If the groundwater table is above one meter below the surface, the water demand by plants is assumed to be satisfied by precipitation and capillary rise. If the groundwater table is lower than 2 m below the surface, capillary rise is neglected. We use a simplified linear function. For an arable land of 10 km^2 with a maximum supplementary irrigation rate of 200 mm/year and the surface level 141.5 m we obtain:

$$dem_{ag}(j) = \begin{cases} 0 & \text{for } h_{ag}(j) \geq 140.5 \\ 89.92 - 0.64 \cdot h_{ag}(j) & [m^3/sec.] \\ 0.64 \ m^3/sec & \text{for } h_{ag}(j) \leq 139.5 \end{cases} \tag{1}$$

Based on the demand function we use the following indicator for the mean *deviation between agricultural water demand and supply* in planning periods:

For the weighting factor we consider the number of years per period

$$\gamma(j) = (i_E(j) - i_B(j) + 1)/i_E(J) \tag{2}$$

$$dev_{ag}(j) = |dem_{ag}(j) - (q_{s,ag}(j) + q_{c,ag}(j) + q_{d,ag}(j))| \tag{3}$$

Total criteria:

$$sdev_{ag} = \sqrt{\sum_{j=1}^{J} (dev_{ag}(j) \cdot \gamma(j))^2} \tag{4}$$

The submodels for the other water users are similar.

Environmental Quality

The state of the environment in the mining region is above all characterized by the water quality in the stream (outflow from the region), in the remaining pit, and in the environmental protection area. The decisive water quality parameters are the Fe^{2+} and H^+ concentrations. Assuming given optimal values for these parameters we define the environmental criteria in terms of the deviation from these optimal values in the mean for planning periods.

$$env_{\alpha}(j) = \frac{1}{2} \sum_{l=1}^{2} \frac{c_{\alpha}(l,j) - optc_{\alpha}(l)}{optc_{\alpha}(l)} \tag{5}$$

$c_a(l,j)$ – concentration of ion l for period j

$optc_a(l)$ – optimal concentration of ion l

Economic Indicators

Our principle economic indicators refer to the economics of mine drainage, economics of water supply and of environmental protection. To characterize the economical efficiency we use a complex index of expenses E. It includes

- the capital investment for technical installations such as drainage wells, pumps, pipelines and water treatment plants, I defines the amortization;

- the maintenance and operational cost of technical installations M;

- benefits B from water allocation for water user. These benefits are fixed by governmental laws. For instance, the mining industry gains for produced drinking water 0.70 Mark/m^3 if the water has drinking water quality, and 0.16 Mark/m^3 if the water needs additional treatment.

All prices used below are based on the price-level of the year 1980. In the socialist economy of the GDR prices are adapted yearly in accordance with the general economic development. This is considered by a yearly price index δ_d = 1.05.

Characterizing economical indicators an important question is their evaluation and comparability in time. Generally, in case of investments for nonprofitable activities (in our case, for example, mine drainage, water treatment, etc.) the respective economic sector is interested to postpone these investments as far as possible. In the mean time the capital saved may be used for other, perhaps, more profitable activities. To model this behaviour we consider an "accumulation factor" δ_a = 1.065. Expenses in later time periods get a lower weight than those in early periods.

Based on this we define the following economical indicator to be minimized

$$E = \sum_i [I(i) + (M(i) + B(i)) \cdot \delta_d^i] \cdot \delta_a^{-i} \qquad (6)$$

The economic indicators are considered for planning periods. To simplify the model description we define weighting factors

$$\delta_1(j) = \frac{1}{i_E(j) - i_B(j) + 1} \cdot \sum_{i=i_B(j)}^{i_E(j)} \delta_a(i)^{-i} \qquad (7)$$

$$\delta_2(j) = \frac{1}{i_E(j) - i_B(j) + 1} \cdot \sum_{i=i_B(j)}^{i_E(j)} \delta_d^i \qquad (8)$$

As a simple example the economic indicator for the agricultural water supply is given.

$$cost_{ag}(j) = \delta_1(j) \cdot (\alpha_{s,ag} + \qquad (9)$$

$$+ [(\beta_{s,ag} + \beta_s) \cdot \mathbf{q}_{s,ag}(j) + \beta_{ag}(\mathbf{q}_{c,ag}(j) + \mathbf{q}_{d,ag}(j))] \cdot 31.5 \cdot \delta_2(j)) \cdot \Delta T_j$$

with $\alpha_{s,ag}$ - specific amortization of the water allocation installation from the stream

$\beta_{s,ag}$ - specific operational cost for the water allocation from the stream

β_s - specific expenses for surface water use
β_{ag} - specific expenses for mine water use.

Descriptors of Systems Development

We distinguish *systems descriptive values* (auxiliary parameters characterizing the systems behaviour in the planning period, not explicitly depending on previous planning periods) and *state variables* (dynamic parameters depending explicitly on the previous planning periods). For the development of the submodels compare the papers Peukert et al. (1985), Tiemer et al. (1985), and Hummel et al. (1985).

Examples for *system descriptive functions* are:

Groundwater flow into Mine D

$$qg_d(j) = a_1(j) + a_2(j) \cdot \Delta \mathbf{tm}_d + a_3(j) \cdot \Delta \mathbf{tm}_d^2 \tag{10}$$

Bankfiltration for a stream segment

$$qi_{6,2}(j) = b_1(j) + b_2(j) \cdot \Delta \mathbf{tm}_d + b_3(j) \cdot \Delta \mathbf{tm}_d^2 \tag{11}$$

Groundwater table in the agricultural area

$$h_{ag}(j) = a_1(j) + c_2(j) \cdot \Delta \mathbf{tm}_d + c_3(j) \cdot \Delta \mathbf{tm}_d^2 \tag{12}$$

Surface water balance profile bp2

$$qi_{1,2} + qi_{6,2} + \mathbf{q}_{s,i} - \mathbf{q}_{c,s} - \mathbf{q}_{i,s} + qs_2 = 4.9 + qs_1 + qs_6 \tag{13}$$

State transition functions have been developed for the water table and water quality in the remaining pit.

Constraints on Systems Development

We have to consider a set of constraints characterizing the water balance for mines (equality constraints) and bounding the decisions. In the following a few examples are given.

Water balance equations for mines, e.g. Mine A

$$wb_a(j) = qg_a(j) - \mathbf{q}_{a,s}(j) - \mathbf{q}_{a,ex}(j) = 0 \quad , \text{ for } j \le j_a \tag{14}$$

Possible groundwater extraction

We assume a fixed construction of the wells for groundwater extraction. Groundwater extraction only then is possible, if the groundwater table is above the well screen. Define with uh_w and lh_w the upper and lower bounds of the height of the screen in all wells and uq_g the maximum well capacity (all wells operate). Assuming a linear distribution of the number of wells within these bounds we get the following constraint:

$$pq_{g,m}(j) = -\frac{uq_g}{uh_w - lh_w} \cdot (h_g(j) - lh_w) + \mathbf{q}_{g,m}(j) \le 0 \tag{15}$$

Constraints on water use because of the water quality (l = 1,2)

These constraints are of the form (e.g. municipal water supply)

$$pq_{6,m}(l,j) = -(uc_m(l) - cg_{61}(l,j)) \cdot \mathbf{q}_{6,m}(j) \leq 0 \qquad (16)$$

with $uc_m(l)$ - upper bound for water quality for municipal water supply

THE DECISION SUPPORT MODEL SYSTEM

Principal Considerations

In the last years the revolutionary development in electronic data processing has opened completely new possibilities for model applications in the practical decision making for large-scale, long-term planning. Otherwise, it is well-known that models for such purposes in the past did not find a wide application and impact in real policy analysis. As the main causes of that we see the following issues:

- Modeler tried to *solve* long-term planning problems, ***anticipating decisions*** of the decision makers, neglecting subjective criteria in the decision making process.

- Generally models developed had to be used by specialists (systems analysts), the decision makers did interact with the model only through those specialists.

- Models frequently did not answer questions asked directly by the decision makers.

"The question, thus, is not whether to model, but how, and, most importantly, how to interface models with our more traditional ways of planning and decision making", Fedra and Loucks (1984). Obviously models or model systems do not replace real-world planning and decision making but should be designed to support them. To be accepted and used by the decision makers such Decision Support Model System must fit in the decision making reality (compatibility with common planning and decision making practice). In order to meet this goal the following principal considerations should be taken into account:

- The underlying mathematical models have to reflect the reality with an accuracy appropriate to the required decisions, but, the models must be simple to be easily handled in a complex model system. Our approaches to these problems are discussed in the papers Hummel et al. (1985), Peukert et al. (1985) and Tiemer et al. (1985). Undoubtedly, the development of simplified models and their verification based on comprehensive models is the most reliable approach.

- The mathematical procedure for multicriteria analysis should be consistent with the policy making reality and should be comprehensible for the model user. With the ***reference point approach***, Wierzbicki (1983), an appropriate method was available (see below).

- The model system should take advantage of the features of modern electronic data processing in order to make it user-friendly, highly interactive, reliable, and flexible. At the end of our paper this topic will be discussed and a few results presented.

Procedure for Multicriteria Analysis

The mathematical model outlined above describes a nonlinear constrained multicriteria problem. For the vector $\mathbf{x}$ of decision variables we obtain the model:

Criteria functions $\min_{\mathbf{x}} \mathbf{f}(\mathbf{x}) = 0$ (17)

subject to

inequality constraints $\mathbf{g}_1(\mathbf{x}) \leq \mathbf{a}$
equality constraints $\mathbf{g}_2(\mathbf{x}) = \mathbf{b}$ (18)
bounds $\mathbf{l} \leq \mathbf{x} \leq \mathbf{u}$

Due to the small number of linear constraints and criteria functions they are considered as nonlinear one.

The analysis is divided into two principal stages (see also Grauer and Kaden (1984)):

- the *exploration* of the range of alternatives,

- the *reference point optimization* in order to obtain a pareto-optimal solution.

For the estimation of the ranges of alternatives each criteria function is optimized separately:

$$\min_{\mathbf{x}} f_i(\mathbf{x}) = \tilde{q}_i \ , \ i = 1, \cdots ,p \quad , \text{subject to (18)} \qquad (19)$$

$\tilde{q}_i$ represents the *utopia* (ideal) *point*. Generally, this point is not attainable, but it may be used as a lower guideline to the sequence of reference objectives. In the same step the *nadir* points as an upper guideline are estimated as the maximum values of criteria functions.

The basic idea of the reference point method is to rank multidimensional decision alternatives $\mathbf{q}$ for decisions $\mathbf{x}$ satisfying the given constraints and bounds (18) relative to a *reference point* (aspiration level) $\bar{\mathbf{q}}$ reflecting the preferences of the decision maker. An achievement scalarazing function $s(\mathbf{q} - \bar{\mathbf{q}})$ defined over the set of criteria $\mathbf{q}$ is associated with each reference point $\bar{\mathbf{q}}$. If we interprete the function $s(\mathbf{q} - \bar{\mathbf{q}})$ as the "distance" between the points $\mathbf{q}$ and $\bar{\mathbf{q}}$, the problem of minimizing this distance might be interpreted as the search for a pareto-optimal point "closest" to the reference point $\bar{\mathbf{q}}$. We use the following funcion

$$s(\mathbf{q} - \bar{\mathbf{q}}) = \left(\frac{1}{p} \sum_{i=1}^{p} w_i^{\rho}\right)^{1/\rho} \ , \ w_i = \delta_i \frac{\tilde{q}_i - q_i}{\tilde{q}_i - \bar{q}_i} \qquad (20)$$

The minimization of Equation (20) subject to (18) results in the pareto-optimal point $\hat{\mathbf{q}}$. δ_i can be used as a weighting factor and ρ is an arbitrary coefficient ($\rho \geq p \geq 2$). For the nonlinear optimization we use the nonlinear programming system MSPN developed at the Institute of Automated Control, Warsaw University of Technology.

Structure and Application of the Model System

The DSMS has been developed in FORTRAN 77 for the VAX 11/780. It consists of 150 modules and consumes approximately 400 KByte storage capacity. In Figure 2 the basic structure of the model system is depicted.

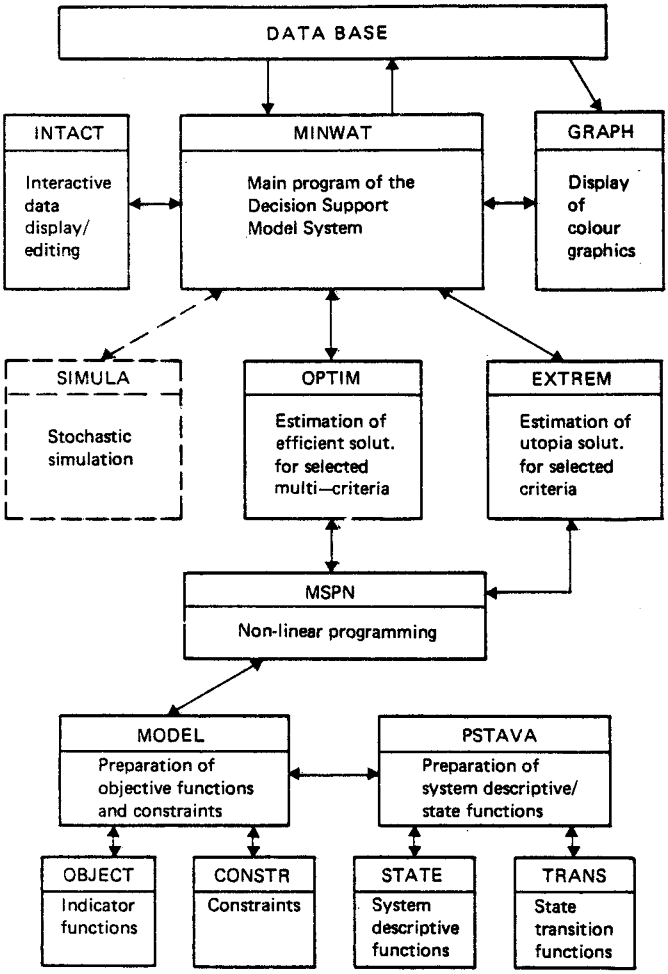

Figure 2: Structure of the model system

The model data are stored in a special DATA BASE. With the subsystem INTACT a simple screen oriented interactive data display and editing is available. Data checks realize the graceful recovery from failures. The system is menu-driven using linguistic elements of the practical language. The subsystem GRAPH realizes the colour graphical display of model results, e.g. the flow chart of the test region (Figure 1). The other subsystems realize the multicriteria analysis (EXTREM, OPTIM), based on the given MODEL. The modular structure ensures an easy model adaptation to different application, supposed they are of a comparable size.

In Figure 3, the interactive model use is characterized. The figure depicts the display on a terminal monitor, the possible alternatives for model users and the activated submodels. Having started the multicriteria analysis of the planning model, the user has to select the criteria for the analysis. For example:

dev-m	deviation municipal water demand/supply [m^3/sec]
dev-i	deviation industrial water demand/supply [m^3/sec]
cost-mi	total mine drainage cost [Mill.Mark]
cost-m	cost municipal water supply [Mill.Mark]
cost-i	cost industrial water supply [Mill.Mark].

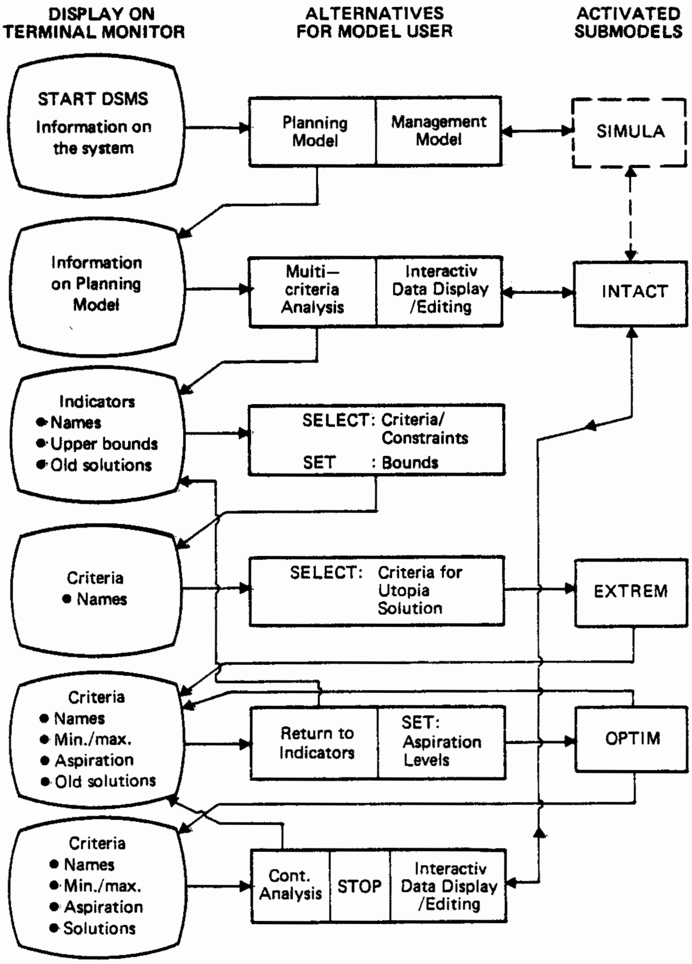

Figure 3: Interactive model use

The next step is the selection of criteria for the utopia solution. After estimation of utopia points within the subsystem EXTREM the user gets information on the criteria and has to set aspiration levels, e.g. the utopia-points (minimum) for all criteria. With the subsystem OPTIM the pareto-optimal solution is computed. Based on these results a new run with different aspiration levels can be done or different criteria for multicriteria analysis might be chosen. Table 2 compares different pareto-optimal solutions for selected criteria for a planning horizon of 10 years (six planning periods).

Table 2: Computational results for different aspiration levels

	Utopia point	Nadir point	Scenario 1		Scenario 2		Scenario 3	
			Aspiration	Solution	Aspiration	Solution	Aspiration	Solution
dev-m	0.0	0.21	0.0	0.04	0.0	0.0	0.1	0.2
dev-i	0.0	0.26	0.0	0.03	0.0	0.0	0.2	0.23
cost-mi	675.3	969.8	675.3	819.5	675.3	813.4	675.3	824.2
cost-m	10.9	96.0	10.9	36.7	50.0	35.0	10.9	17.9
cost-i	194.3	389.0	194.3	288.1	350.0	293.0	194.3	280.6

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