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The purpose of the present publication is to popularize information tools and applications of informatics in environmental engineering and environment protection that have been investigated and developed in Poland and Germany for the last few years. The papers published in this book were presented during the workshop organized by the Leibniz-Institute of Freshwater Ecology and Inland Fisheries in Berlin in February 2006. The problems described in the papers concern the mathematical modeling, development and application of computer aided decision making systems in such environmental areas as groundwater and soils, rivers and lakes, water management and regional pollution. The editors of the book hope that it will support the closer research cooperation between Poland and Germany and when this intend succeeds then also next publications of the similar kind will be published.

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CHAPTER 3

Water management and Decision support

ANALYZING WATER MANAGEMENT STRATEGIES IN URBAN REGIONS BY DIRECTED GRAPHS

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Abstract: *In contrast to conventional multicriteria decision aids, such as the well known PROMETHEE approach, AHP or SMART, the different versions of ELECTRE, we take the point of view of environ metrics: Let first the data speak, and then let us include subjective preferences in order to get a unique decision. In the present paper we introduce an improved version of the decision support system METEOR (Method of evaluation by order theory). The basis of the method is a data matrix, whose objects are characterized by a set of indicators. By means of the indicators a partial order is derived. In subsequent steps indicators are aggregated by a weighting procedure, allowing a high degree of participation of stakeholders and other participants of the planning process. The aim of METEOR is to find finally either a linear order or (in order theoretical terms) a greatest element, i.e. an object which is the best in comparison with all others.*

As example we evaluate the effects of nine water management strategies on the complex surface water system in the cities of Berlin and Potsdam. The nitrogen concentration in four river sections is used as the only one type of indicator. As this indicators nevertheless refers to different river sections, the ranking analysis belongs still to multicriteria procedures.

Keywords: Water management, evaluation, decision support, posets, Hasse diagrams.

1. Introduction

Decisions concerning management of surface waters need to be supported by information about potential chemical pollution. Especially in cities, a spatial and temporal exposure pattern of various substances is to be expected for both inorganic and organic toxicants as well as nutrients and heavy metals. To evaluate the chemical pollution of surface waters, many methodological approaches are available, requiring in principle the same working steps (Klauer et al., 2001):

1. The definition of options, in our case water management strategies, which are to be evaluated and the generation of a set of indicators, appropriate for evaluation of options with respect to a certain goal, such as environmental hazards. The number of options and *if* indicators defines the dimension of the decision matrix.

2. Modelling the effects of the options and hence the numerical values of thje entries of the decision matrix..
3. Evaluation of the options, for example by powerful algorithms supporting the process of decision making such as PROMETHEE (Brans & Vincke, 1985), AHP (Analytic Hierarchy Process, Saaty, 1994), MAUT (Schneeweiss, 1991), ELECTRE (Roy, 1990) or NAIADE (Matarazzo & Munda, 2001).

The third step, the algorithmic aspect of evaluation, is often almost disregarded in real decisions, yet can be considered to be just as important as the first two steps: The chosen evaluation approach will strongly influence the evaluation result and the extent of the participation of stakeholders. The benefit of participation of stakeholders in turn depend on the transparency of the evaluation procedure. As more indicators are involved in the evaluation procedure as more difficult it is to trace back the impact of the data and to model the preferences. For example: Decisions about complex problems such as water management will include conflicting indicators. To solve such conflicts, the most commonly used approaches within decision support systems (DSS) listed above, include a methodological step of indicator's aggregation. The benefit of the aggregation step is that finally a linear ranking of the options can be obtained, identifying one best solution. Aggregation of indicators is one example to model the preferences. Aggregation of indicators, however implies a compensation among them: a bad evaluation in one or more indicator(s) can be compensated for by a good evaluation in other indicators. This compensatory effect is in many cases needed as indeed a decision must resolve trade-offs. However, as indicators can represent fundamentally different aspects such as ecology and economy, compensation can be considered as a comparison of "pies to apples". For these reasons, researchers and stakeholders complain about the "weighting camouflage" in decision support (Strassert, 1995). An alternative approach is provided by simple elements of partial order theory, such as Hasse Diagram Technique (HDT) (Brüggemann et al., 1994, Brüggemann et al., 2001, Patil et al., 2005). The Hasse diagram technique avoids consequently any aggregation of indicators. Therefore it is a transparant method. However the price is that often no decision is possible. This disadvantage avoids METEOR: It is still transparent as its core is still the Hasse diagram technique; however it is possible to derive a linear rank order and hence provide a unique decision.

2. Hassediagram technique and METEOR

Both methods, HDT and METEOR are explained and extensive literature is available (HDT: see for example Brüggemann et al., 2001 and the references given there; METEOR, see Simon et al., 2005; Voigt& Brüggemann, 2005 for recent publications). However for the sake of convenience for the reader some basics should be introduced here: As a methodological precondition of HDT, all indicators need to be orientated consistently in such a way that, for example, small numbers always represent a good rating. Options are sorted on the basis of a simple simultaneous ≤-

comparison of all indicator values of any of two options. The resulting graph can be considered as a digraph, which has no cycles and -as ordinary graph has no triangles because usually a transitivity reduction has been performed to obtain the Hasse diagram. For details of drawing Hasse diagrams the reader may consult the literature, for example (Brüggemann, Voigt, 1995). HDT provides several tools for convenient and detailed data analysis such as the sensitivity of the structure of the digraph with respect to the presence or absence of different indicators or by poset dimension theory the identification of latent attributes, see Brüggemann et al., 2001. However, as in HDT no compensation among indicators is carried out at all, conflicting evaluations of indicators cannot be methodologically removed. Consequently multiple favourable options can be identified as incomparable winner solutions.

METEOR (Method of evaluation by order theory), attempts to resolve the dilemma among obtaining a clear decision (one best solution), maintaining transparency and allowing participation, e.g. by the weighting of indicators. METEOR is based on the well known and often used concept of a hierarchy of criteria in multicriteria decision aids (see e.g. Brüggemann et al., 1999). METEOR allows a step-by-step aggregation of indicators by forming weighted sums about subsets of indicators. One may firstly aggregate indicators related to similar impacts, then proceed to higher levels of the hierarchy of criteria. The possibility of step-by-step aggregation of indicators provides the freedom to thoroughly analyse the effects of indicator weights and compensation. Furthermore, preferences (indicator weights) which are most sensitive to the evaluation result can be easily identified. Here, the application of the METEOR approach is exemplified by the evaluation of the effect of nine water management strategies on the chemical pollution of the surface water system of the adjacent cities of Berlin and Potsdam, with an emphasis on nutrients. Originally four different types of indicators, each referenced to the river sections of the region Berlin/Potsdam, where estimated and the scenarios evaluated by them (Simon et al, 2004 a,b and 2005). Here in order to demonstrate a methodological aspect we restrict ourselves on only one type of indicator, namely the Nitrogen concentrations estimated by the model MONERIS (MOdelling Nutrient Emissions in RIver Systems, Behrendt et al., 1999, 2000). As this indicators refers to several river sections we are still confronted with a multicriteria problem.

3. Material and methods

Study site, water management strategies and indicators

The study site is the region Berlin and Potsdam in Germany (Figure 1). Its main rivers are Havel, Spree and Dahme (for a more detailed description, see Simon et al., 2004). In order to define geo-referenced indicators the surface waters are divided into 14 river sections. Altogether nine water management strategies referring to the surface water system of the adjacent cities of Berlin and Potsdam are to be evaluated. (the full analysis: see Simon et al., 2004 a,b)

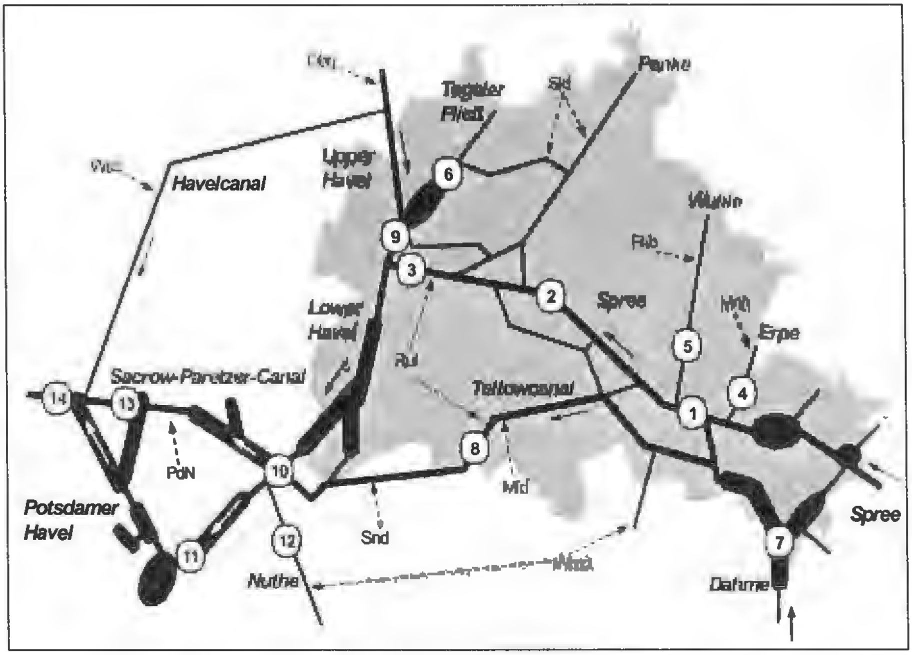


Figure 1. Schematic diagram of the surface water system of Berlin and Potsdam. Numbers describe different river sections, Fkb, Mfd, etc are waste water treatment plants. Dashed lines show wastewater pipe lines. Shaded area = city of Berlin.

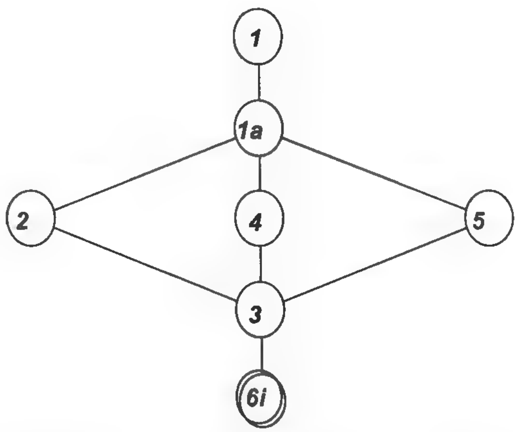


Figure 2. Hasse diagram of 9 scenarios, applying indicator N on different river sections, namely N_1, N_2, N_3, and N_{10}, Note that there is an equivalence class "6" = {6i, 6ii, 6iii} of which a representative element, 6i, is shown in the Hasse diagram.

Table 1. Water management strategies

<table>
<tr><th rowspan="2">Scenarios</th><th rowspan="2">hydrological boundary conditions</th><th colspan="2">waste water treatment</th><th rowspan="2">entry of storm water</th></tr>
<tr><th>purification technique</th><th>closing of waste water treatment plants</th></tr>
<tr><td>1a</td><td colspan="4">current state (average of the years 1993-1997)</td></tr>
<tr><td>1</td><td rowspan="2">reduced amount of water</td><td></td><td></td><td></td></tr>
<tr><td>2</td><td>technical upgrade</td><td rowspan="2">Fkb, Mfd, Obg</td><td></td></tr>
<tr><td>3</td><td rowspan="6">reduced amount of water and lower nutrient concentrations</td><td rowspan="3">advanced waste water treatment (micro-filtration)</td><td rowspan="6">emission 50% reduced</td></tr>
<tr><td>4</td><td>Mfd, Odg</td></tr>
<tr><td>5</td><td rowspan="2">Fkb, Mfd, Obg</td></tr>
<tr><td>6i</td><td rowspan="3">alternative sanitary technique</td></tr>
<tr><td>6ii</td><td>Mfd, Obg, Mnh, Snd</td></tr>
<tr><td>6iii</td><td>Mfd, Obg, Mnh, Sld</td></tr>
</table>

Figure 2 shows that the optimal scenarios are those of the equivalence class "6", where alternative sanitary concepts are presumed. The aim of the decision support system is almost fulfilled: We have found three scenarios which are optimal, and which are equivalent with respect to the Nitrogen concentrations in the four river stretches. However the concepts behind 6i, 6ii and 6iii are quite utopic therefore other scenarios may also be of interest. As here scenario 2, 4 and 5 are mutually incomparable we apply METEOR to find out which of these both scenarios may be preferred and to explain new methodological steps. As the four indicators are of the same scaling level type, namely metric indicators, numerical aggregations are not restricted. Most promising aggregation is to start with those indicators, which bear the highest conflict potential. Corresponding to the Spearman correlation the lowest value is found for the indicator pair N_1, N_2. A first model to be analyzed in METEOR is given by equations (1) - (3) (model I):

$$N_{1,2} = g_1 * N_1 + (1-g_1) * N_2 \quad (1)$$

$$N_{3,10} = g_2 * N_3 + (1-g_2) * N_{10} \quad (2)$$

$$0 \leq g_1, g_2 \leq 1 \quad (3)$$

A study with one indicator and four river sections

In order to demonstrate the philosophy behind METEOR the river sections 1, 2, 3 and 10 of the region of Berlin were selected (see Figure 1) and as the only indicator the nitrogen concentration "N". The data matrix is shown in Table 2:

Table 2. Nitrogen concentrations in sections 1, 2, 3 and 10 of the city of Berlin (see Figure 1)

Indica-tor/scenarios	N_1	N_2	N_3	N_{10}
1a	3.03	4.45	5.05	5.90
1	3.40	4.96	5.62	5.90
2	3.03	3.0	3.65	4.70
3	2.70	2.6	3.65	3.77
4	2.70	3.30	4.18	3.77
5	3.03	3.00	3.89	3.77
6i	2.50	2.60	2.83	2.50
6ii	2.50	2.60	2.83	2.50
6iii	2.50	2.60	2.83	2.50

The Hasse diagram based on all four indicators N_1, N_2, N_3 and N_{10} is shown in Figure 2.

By the new attributes $N_{1,2}$ and $N_{3,10}$ new directed graphs of order relations is induced. These Hasse diagrams depend on the actual values selected for g_1 and g_2 in model I. According to (1)-(3) any comparability among the scenarios 1 to 6iii will be preserved, therefore the new poset is related to the original one (based on N_1, N_2, N_3 and N_{10}) by an order preserving map. Just three incomparabilities, namely scenario 2 vs 4, scenario 2 vs 5 and scenario 4 vs 5 may be transferred into a comparability by (1)-(3).

The system of digraphs is shown in Figure 3. The systematic and contuinuous variation of the weights may theoretically lead to 8 cases, according to arbitrary selecting a > or < -relation. However, due to the transitivity constraint and due to possible ties the g_1,g_2 variation leads to only 5 different posets (Figure 3). In Figure 4 the results of this analysis is shown; as there are two weights, g_1 and g_2 which can be indepently varied, we consider them as coordinates. The analysis is performed in the positive orthant, which we also call a "g-plane". We concentrate ourselves on the relation between scenarios 4 and 5.

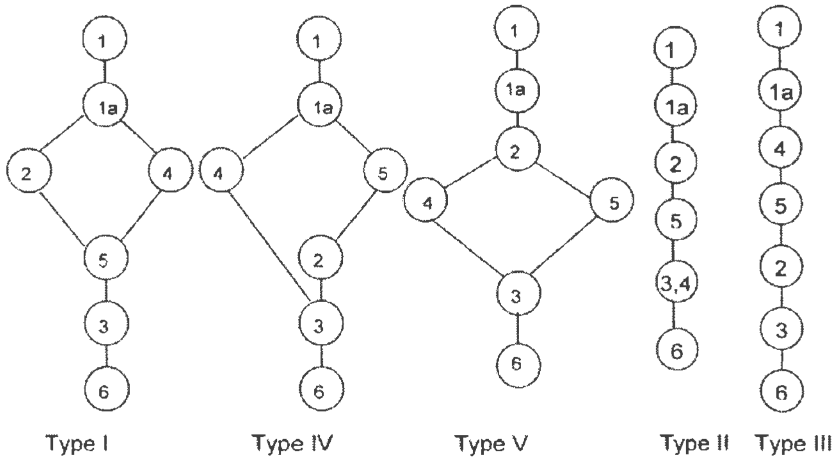


Figure 3. Five types of orders appear, if g_1, g_2 are independently from each other varied taking however care for the constraint $0 \leq g_1, g_2 \leq 1$.

From Figure 3 we learn that there are different positions of scenario 5 (Figure 3, Type I to Type V) and especially that once 5 > 4 ("5 wins"), once 4 > 5 ("4 wins") and once 4 || 5 (the sign || denotes an incomparability; in Figure 4 we describe the incomparability of scenarios 4 and 5 as "indifferent"). Figure 4 provides an overview about the different ranking results:

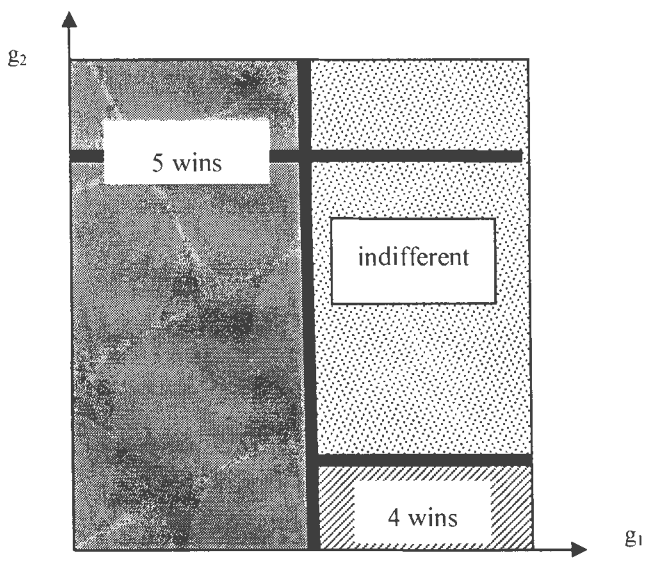


Figure 4. Preferences are introduced by model I: Order relations between scenario 5 and 4.

Methodologically, this analysis has shown:

1. We can consider different fields of the g-plane as "stability fields" or in the context of physical chemistry "phases", where independent on the values of the pair g_1, g_2 the same partial order is found. The extent of these stability fields i.e. the position of the g-values, where a transition appears depends mainly on the numerical values of the indicators.
2. The transition from one field to another one can be considered as "phase transition". Hence decision analysis by METEOR should be seen in the context of stability fields and their boundaries.
3. The boundaries should be parallels to the g_i-axes, because any condition about $N_{1,2}$, $N_{3,10}$ leads separately for each g_i to a numerical constraint. In other aggregations, where for example three indicators will be aggregated to one, there will be relations among the weights, such that the boundaries will have some slopes $\neq 0$ or $\neq \infty$ (see the next study).

In order to exemplify item (3) we constructed another model (model II):

$$N_{City} := g_1*N_1+g_2*N_2+g_3*N_3 \quad (4)$$

$$N_{out} := N_{10} \quad (5)$$

$$\sum g_i = 1 \quad (6a)$$

$$0 \leq g_1, g_2, g_3 \leq 1 \quad (6b)$$

The posets induced by N_{City}, N_{out} depend on the values of the weights g_i (under the constraint (5)) and are also related to the original poset (Figure 2) by an order preserving map. The aggregation (4) maps the poset, induced by $\{N_1, N_2, N_3\}$(see Figure 5) into a linear order which also preserves all its comparabilities.

Trivially the indicator N_{out} ($= N_{10}$) induces a linear order (exactly a preorder because of different ties) as follows:

$$1a, 1 > 2 > 3, 4, 5 > 6 \quad (7)$$

As N_{out} does not differentiate between scenarios 4 and 5, the posets, induced by $\{N_{City}, N_{out}\}$ will in some cases (depending on the weights g_i) exhibit the relation 4>5 and in some others the reverse relation 5>4. Furthermore in allmost all cases discussed in Table 3 there will be an incomparability 2 || 5. This incomparability arises from N_3: With respect to N_1 and N_2 the scenarios 2 and 5 are equivalent, and only N_3 leads to 5>2. Together with N_{out}, where $N_{out}(5) < N_{out}(2)$ (see Table 2) an incomparability must hold. The only exception is. when N_3 is considered as completely unimportant ($g_1 = g_2 = 1$ hence $g_3 = 1-g_1-g_2 = 0$).

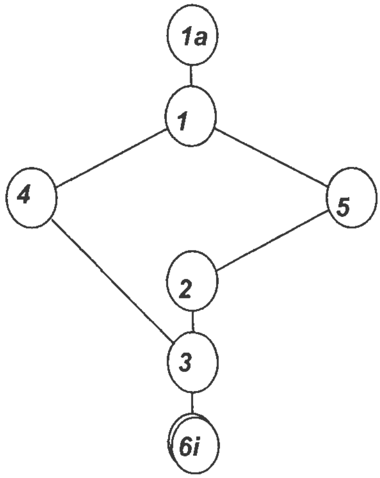


Figure 5. The partial order of nine scenarios, induced by N_1, N_2, N_3. Note that the equivalence class "6"= {6i, 6ii, 6iii} is represented by 6i.

When do these cases appear? This depends on the actually selected weights. Only in one case we know in advance what will happen: As we know from the discussion above, only if $g_3 = 0$ then the rank due to N_{out} gives the relevant information, namely 2>5. The result may be drawn in a 3-dimensional coordinate system, due to three different weights. Schematically Figure 6 is obtained:

One boundary of the accessible g_i-values, namely the boundary g_3=0 leads to 2>5, whereas inside of the accessible area, there must be 2 || 5 and whether 4>5 or 5>4 or 4>2 or 4<2 depends on the weights. As in Figure 4 there are critical g_i-values where a transition from one poset to another will appear. For a graphical representation we select the coordinate system by g_1 and g_2, under considering the constraints (6). Figure 7 shows the results. Note that the boundaries of the different stability fields of the posets are only schematically drawn. The exact equations can be easily obtained from the model equations themselves.

The boundary, given by g_3=0 is drawn as a double line. Depending on g_1 along this boundary two different posets appear (one with 2 || 4 , 2 > 5, 4 >5 (low g_1 - values) and another one: 2>5>4 (large g_1-values)). Therefore one part of the double line is dashed. In the remaining inner part of the g_1, g_2-orthant three different posets appear:

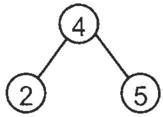
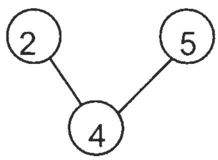
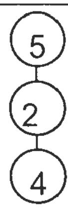
(1) 2 || 4, 2 || 5, 4 > 5 small g_1-values

(2) 2 || 4, 2 || 5, 5 > 4 medium g_1-values

(3) 2 > 4, 2 || 5, 5 > 4 large g_1-values

As there are two incomparabilities i.e. 4 || 2, 4 || 5) there are the following linear orders possible (Table 3):

Table 3. Analysis of the relations among scenarios 2, 4 and 5 due to the aggregation (4).

4 in relation to 2	4 in relation to 5	tentative diagram	poset, obtained by taking into account: 5>2 (see Figure 5)
>	>		
>	<		
<	>		Contradiction to 5>2, hence the tentative diagram is to be rejected
<	<		

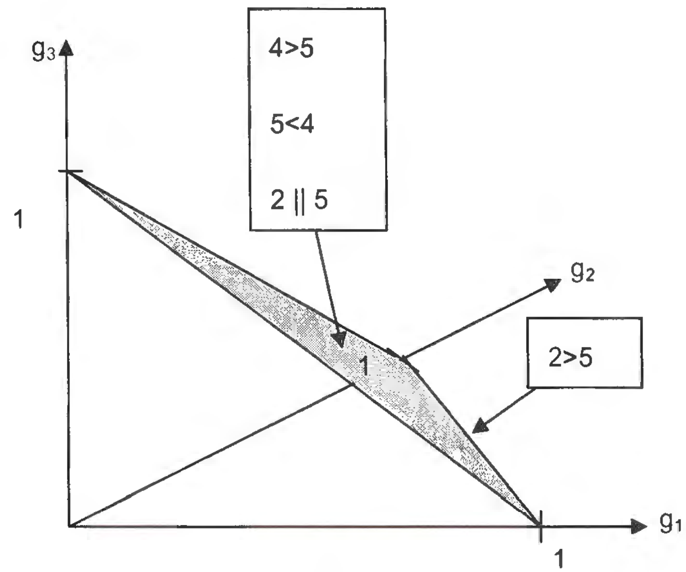


Figure 6. The "g-space" and the constraint (6a). Possible configurations of the poset.

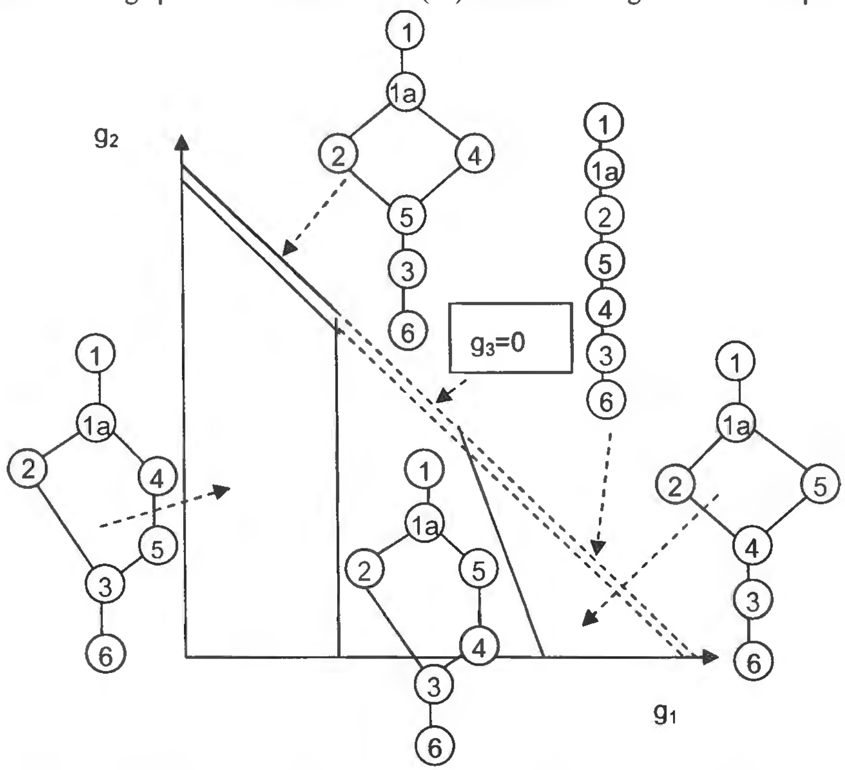


Figure 7. Schematic representation of the results, obtained from the model II (4)-(6).

Low values of g_1 favour the scenario 5. This is consistent with the finding in model I, as again a low preference of river section 1 leads to a preference of scenario 5 over scenario 4.

The essential information is about the three incomparabilities. One may draw a still more schematic diagram as follows (Figure 8):

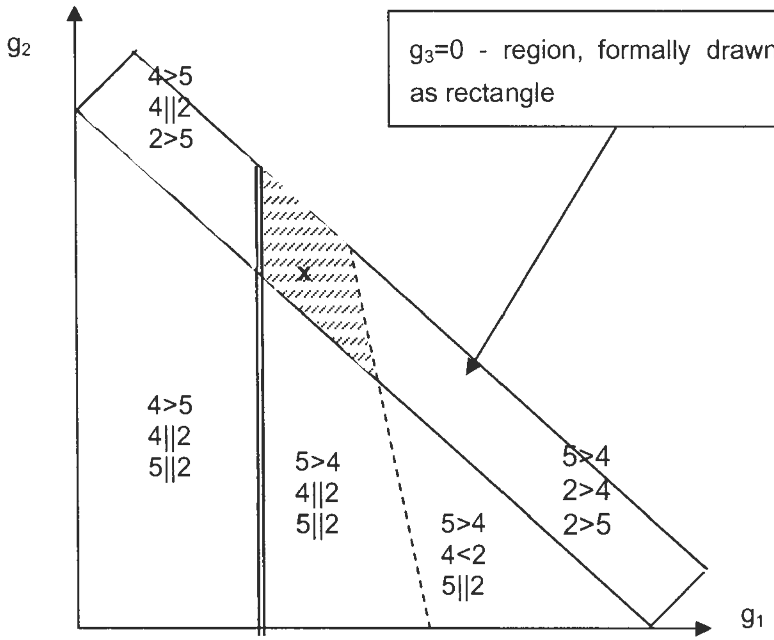


Figure 8. Stability fields . Note that the region "x" is in reality extremely small, the poset belonging to this region could not identified yet. The double-line marks the g_1, g_2 - combinations where the order reversal 4>5 - 5<4 happens. The dashed line: Transfer: 4 || 2 to 4 || 2.

4 Summary and future aspects

The stepwise aggregation by METEOR allows to trace back the effect of subjective weightings of indicators. Performing step by step aggregation often one obtains as intermediate results partial orders which are enriched in comparison to the poset of the initial problem. In this paper just these intermediate posets are more closely examined. It turns out that the concept of stability fields is rather useful, as this concept makes evident, that often a high degree of variation of the weights is possible, without an effect on the resulting Hasse diagram. If one takes the point of view of probabilities, then one may draw a set of g_i-values, fulfilling the constraints (6a) and (6b) and one may calculate the probability for a certain order or even for a whole posetic configuration. Therefore the extent of stability fields is of definite interest, as they are proportional to the probability to obtain a certain posetic configuration. In the model II (4)-(6a,b) it turns out that some stability fields can be characterized by a lower algebraic dimension than the others: Here for example segments of the $g_3=0$ line. This affirms the concept of "stability", as any trial, where by chance $g_3 \neq 0$ would lead to an incomparability, namely 2 || 5.

From a practical point of view, the analysis of the results of intermediate steps of indicator aggregation can be performed as follows:

1) Check the initial poset for the incomparabilities among the objects (here: among the scenarios).
2) Check all the posets, which can be formed from intermediate steps of indicator-aggregation. The result should be to identify, which of the incomparabilities found in 1) may remain and which may be transferred to comparabilities.
3) If several comparabilities are obtained in step 2 then the transitivity must be taken into regard. If for example 2 > 5 and at the same time 5 > 4 then the transitivity of the order relation demands 2 > 4.
4) If "phase transfers" appear, then the crucial weight-combinations can be obtained by analysis of the aggregation model: If for example $N_{City}(x) > N_{City}(y)$ holds in one stability field, and in another one the reverse order, then the transition will appear for those weight-combinations where $N_{City}(x) = N_{City}(y)$. As in general in the model for N_{City} there are three weights together with a normalization constraint (i.e. equations (6a) and (6b)), one will find a relation among the three weights: $f(g_1,g_2,g_3) = 0$. This relation will be linear, because we supposed a linear model.
5) If models are formed where more than three weights are considered to model a superattribute then the geometry of the stability fields will get quite complex. One of the most important future tasks is to find methods to characterize these stability - fields having an algebraic dimension > 2.

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MODELLING CONCEPTS AND DECISION SUPPORT IN ENYIRONMENTAL SYSTEMs

This book presents the papers that describe the most interesting results of the research that have been obtained during the last few years in the area of environmental engineering and environment protection at the Systems Research Institute of the Polish Academy of Sciences in Warsaw and the Leibniz-Institute of Freshwater Ecology and Inland Fisheries in Berlin (IGB). The papers were presented during the First Joint Workshop organized at the IGB in February 2006. They deal with mathematical modeling, development and application of computer aided decision making systems in the areas of the environmental engineering concerning groundwater and soil, rivers and lakes, water management and regional pollution.

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