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Multicriteria analysis under uncertainty with IANUS – method and empirical results

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Summary

IANUS is a method for aiding public decision-making that supports efforts towards sustainable development and has a wide range of application. IANUS stands for '**I**ntegrated **A**ssessment of Decisions u**N**der **U**ncertainty for **S**ustainable Development'. This paper introduces the main features of IANUS and illustrates the method using the results of a case study in the Torgau region (eastern Germany). IANUS structures the decision process into four steps: scenario derivation, criteria selection, modeling, evaluation. Its overall aim is to extract the information needed for a sound, responsible decision in a clear, transparent manner. The method is designed for use in conflict situations where environmental and socioeconomic effects need to be considered and so an interdisciplinary approach is required.

Special emphasis is placed on a broad perception and consideration of uncertainty. Three types of uncertainty are explicitly taken into account by IANUS: development uncertainty (uncertainty about the social, economic and other developments that affect the consequences of decision), model uncertainty (uncertainty associated with the prediction of the effects of decisions), and weight uncertainty (uncertainty about the appropriate weighting of the criteria).

The backbone of IANUS is a multicriteria method with the ability to process uncertain information. In the case study the multicriteria method PROMETHEE is used. Since PROMETHEE in its basic versions is not able to process uncertain information an extension of this method is developed here and described in detail.

1 Introduction: The scope of IANUS

On the road to sustainable development, public decision-making should take responsibility for our fellow humans, future generations and the environment (WCED 1987: 42). Acting responsibly means taking the foreseeable consequences into account, albeit without forgetting that not all the consequences of current decisions can be known (Klauer 1999: 118-119). But how can we deal with uncertainty and ignorance? How can conflicts of interests be solved and good decisions made?

IANUS is a tool that supports the making of public decisions in conflict situations with considerable and important consequences. It was developed during a four-year interdisciplinary project on land-use conflicts between the protection of water resources and economic development in the Torgau region – a rural region in eastern Germany (Horsch et al. 2001, Klauer, Meyer et al. 2001). IANUS stands for **I**ntegrated **A**ssessment of Decisions u**n**der **U**ncertainty for **S**ustainable Development.[1]

The main function of IANUS is to structure the decision process. IANUS provides a framework for the integration of separate models for estimating the consequences of potential actions as well as methods to evaluate these consequences. Its overall aim is to extract in a clear, transparent way the information needed for a sound and responsible decision from a complex conflict situation. IANUS has been designed to provide practical support for public decisions in conflict situations where environmental and socioeconomic effects are to be considered and so an interdisciplinary approach is needed. Special emphasis is placed on a broad perception and the consideration of uncertainty. Except for trivial cases, uncertainty is ubiquitous in decision-making. A good decision support tool provides the decision-maker with information about the uncertainty involved. Moreover, the tool should produce its results in a way which is transparent and easy to understand for outsiders in order to promote acceptance among the decision-makers as well as the other stakeholders. These are requirements which are all met by IANUS and in this respect it is a tool to promote the ideal of sustainable development. One aim of this paper is to introduce the main features of IANUS. A second aim is to show how the method was applied to the concrete conflicts of the case study in the Torgau region.

The backbone of IANUS is a multicriteria method with the ability to process uncertain information. Multicriteria analysis (MCA) (e.g. Vincke 1992, Munda et al. 1994, Roy 1996, Salminen 1998) is regarded as an alternative to the traditional economic decision tool, benefit-cost analysis, for complex decision problems (Joubert et al. 1997, O'Connor 2000). Different effects are measured on different dimensions (criteria), which allows trade-offs and decision conflicts to be explicitly analyzed (e.g. Matrinez-Allier et al. 1998). This usually requires the participation of the various stakeholders and interest groups in the decision process (Roy 1990; De Marchi et al. 2000). In this paper, the multicriteria method PROMETHEE (Brans and Vincke 1985) – an so-called outranking method – is used. Since PROMETHEE in its basic versions is not able to process uncertain information an extension of this method is developed here.[2] The description of this extension is a third aim of the paper. Yet note that IANUS is not tied to one specific multicriteria method like PROMETHEE. Its key characteristics are the structuring of the decision-making process,[3] the way it integrates uncertainty issues, and the usage of models to predict the effects of the alternatives.

The paper comprises conceptual aspects (framing the decision process with IANUS), technical aspects (the extension of PROMETHEE for uncertainty) as well as empirical aspects (the case study). In the following we proceed like this. In Section 2 we describe the land-use conflicts in the Torgau region used later on for illustrative purposes. Then we explain in Section 3 how IANUS structures the decision-making process into four steps. Section 4 recounts why we chose PROMETHEE as the method to aggregate monocriteria evaluations to produce a final recommendation in the case study. Section 5 elucidates how uncertainty is treated in IANUS at the various stages of the decision-making process. In particular we precisely describe how PROMETHEE is extended to deal with uncertainty. Finally, the results of applying IANUS to the Torgau case study are presented and discussed in Section 6.

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[1] Ianus is the Roman god who symbolizes beginning. He has two faces, one looking forward into the future, and the other looking back. The month of January is named after him.

[2] Apart from multiple attribute utility theory, only few multicriteria methods have been developed to cope with uncertainty (Vincke 1992). Exceptions are D'Avignon and Vincke (1988) who have designed a probabilistic outranking procedure and Munda (1995) who extended NAIADE in order to cope with fuzzy information.

[3] Roy organizes his book (Roy 1996) following a similar structuring of a decision making process. Another structuring of a decision making process which is however focused on the application of benefit-cost analysis can be found in Hanley and Spash (1993: 8-20). What distinguishes IANUS from these approaches is above all the special emphasis on uncertainty and on integrating modeling from different disciplines that leads to the concept of framework of development (see Messner, Klauer et al. 2001 and Section 3).

2 Land-use conflicts in the Torgau region

In the Torgau region (Saxony, eastern Germany) there is a pressing land-use conflict between groundwater protection and economic development. The debate on reducing wellhead protection zones in eastern Germany resulted from the sharp decline in the demand for water after German reunification in 1989. The main reasons for this lower demand were the far-reaching deindustrialization and the reduced water losses in the distribution network following extensive repair work.

The Torgau region has a size of approximately 700 km^2. This rural and in economic terms poorly developed area is crossed by the River Elbe – after the Rivers Danube and Rhine the third biggest river in Germany. In the Torgau region, drinking water is extracted for the long-distance water supply company Elbaue–Ostharz GmbH, which supplies about 600,000 m^3 of drinking water per day to a population of 3.5 million. Torgau Waterworks has the capacity to contribute about 40% of this volume. To protect the groundwater, 33% of the 686 km^2 of the district of Torgau has been declared wellhead protection zones. In addition, 52% (partly overlapping with the wellhead protection zones) is identified as landscape and nature protection zones. Agriculture, industry, and gravel-mining are subject to various restrictions within the protection zones.

Under these circumstances, local politicians and economic pressure groups argued that the wellhead protection zones obstructed several economic activities and hence hampered the economic development of the region. The main land-use conflicts in the Torgau region are between drinking water protection and:

- *agriculture*: bound by certain conditions and restrictions on cultivation and pasturing;
- *sand and gravel mining industry*: excavation only allowed (if at all) within the outer zones of the wellhead protection zones;
- *construction of infrastructure (roads, sewers etc.)*: subject to certain restrictions and hence saddled with additional costs;
- *settlement of new industry and other business*: may opt for other locations given the scarcity of building land and restrictions within the protection zones (Horsch and Ring 2001: 23-29).

IANUS was used in the case study to analyze and evaluate different ways of alleviating the conflicts in the region. The public authorities unexpectedly decided to reduce the protection zones shortly before the research project was finished. Therefore the final results of this study should be regarded mainly as a policy evaluation rather than policy advice. Although the land-use conflicts in the Torgau district are employed here to illustrate our decision support approach, the methodology is not restricted to the conflict between groundwater protection and economic development, but also provides a framework for assessing a wide range of land-use and other environmental conflicts and advising decision-makers.

3 Four steps of IANUS applied in the Torgau case study

The methodological procedure when using IANUS can be divided into the four steps described below along with their application in the Torgau case study.

3.1 Step 1: Problem definition and scenario derivation

Using the IANUS method starts with a careful analysis of the conflicts existing in the region of interest. The potential *fields of action* and appropriate *options* for resolving the conflict situation are identified with local stakeholders. A combination of options from each of the relevant fields of action is called an *alternative*. It is the set of possible and relevant alternatives that is the subject of evaluation. IANUS is restricted to consideration of a finite number of alternatives.

In the Torgau region, work to reduce the complexity of the conflict and to isolate the alternatives began with an early meeting with important stakeholders. After several group and individual interviews and discussions with different stakeholders and stakeholder groups, two fields of actions appropriate to settle the local conflict were identified. The first field of action was ‘groundwater protection’. In the region controversy raged over whether a certain wellhead protection zone should be reduced in size by the regional authorities (option 1) or not (option 2). The second field of action was ‘gravel mining’ with the options of opening up new gravel mining pits in the region (option 1) or not (option 2). The combination of the options of the two fields of action resulted in four alternatives which were to be assessed later on. They read:

Alternative 1: retention of wellhead protection zones and additional gravel mining pits

Alternative 2: reduction of wellhead protection zones and additional gravel mining pits

Alternative 3: retention of wellhead protection zones and no additional gravel mining pits

Alternative 4: reduction of wellhead protection zones and no additional gravel mining pits

These alternatives represent the potential ways to solve the regional problem.

However, the assessment of these alternatives depends not only on the alternatives themselves, but also on the context in which the alternatives are considered. For instance, the welfare effects of economic restrictions due to a wellhead protection zone may be more pronounced under thriving economic conditions than at times when the economy is stagnant. As a result, one crucial aspect of the IANUS methodology is to define different *frameworks of development* that include important future developments regarding economic development, social life, environmental circumstances, etc. as well as anticipated reactions and adaptations by consumers and firms to decisions. Since these frameworks of development cannot be influenced by the regional authorities, they are considered to be externally set. They enable the alternatives under investigation to be studied in the context of different circumstances. In other words, instead of the assumptions underlying the predictions of the effects of alternative actions being fixed, a variety of reasonable assumptions is investigated. Proceeding thus allows including certain aspects of uncertainty over future developments in the analysis (see below Sec. 5.2).

In the Torgau case study several different issues[4] were considered in the definition of three frameworks of development: REALO for a realistic development path, BOOM for a very optimistic future economic development, and STAGNATION for a stagnant economic path. In the IANUS methodology, one alternative considered under one specific framework of development is called a *scenario*. Thus, having defined three frameworks of development and four alternatives, twelve scenarios were derived for the Torgau case study (see Messner, Klauer et al. 2001 for details).

Step 1 of IANUS, which essentially covers the problem definition, is certainly the step where the involvement of the decision-makers as well as local experts and stakeholders is most necessary.

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[4] Population development, economic growth, gravel demand, drinking water demand, intensity of agricultural production, forest conversion, reforestation and land sealing as well as adjustments by farmers, gravel-mining firms and other economic actors.

3.2 Step 2: Selection of problem-specific evaluation criteria

Working towards the overall concept of sustainability, the criteria should be chosen by stakeholders with the assistance of the analysts such that they appropriately reflect the scenarios' economic, social and ecological effects. Furthermore, they need to be suitable for the models and methods available for estimating the scenarios' effects. In the Torgau project, an interdisciplinary committee including local stakeholders worked out five criteria (see Table 1 and Klauer, Messner et al. 2001 for details). Inserting the criteria into the columns of a matrix and the scenarios into the rows produces a multicriteria matrix.

Table 1: The five evaluation criteria in the Torgau case study.

Category	Criterion	Explanation and justification
Economic criteria	Benefits minus costs (net-benefits)	Measures the welfare effects of a decision. It is calculated by means of benefit-cost analysis.
	Gross value added	Is an indicator for the economic performance of a region.
Social criteria	Number of employees	This number frequently plays an outstanding role in political discussions and partly reflects the social state of a region.
Ecological criteria	Nitrate concentration in the percolation water	Nitrate is the most important pollutant in regions where agriculture affects the environment. The amount of nitrate in the percolation water is a good indicator of its environmental impact.
	Qualitative environmental impact assessment of gravel mining	Exploring for gravel irreversibly changes the landscape as well as ecosystems. Assessment is done by experts. Possible marks were 'good', 'mean' and 'bad'.

3.3 Step 3: Modeling and Estimation of Scenario Effects

The third step of the IANUS method involves the scientific modeling and estimation of the scenario effects. In the Torgau case study, the economic analysis consisted of regional sectoral effect analyses and a dynamic input-output model designed to reflect the interconnections between the various economic sectors. The input-output model enables the direct and indirect effects of land-use changes on economy and society to be estimated (gross value added, employment figures) (Klauer 2001). The input-output model was fed with the results of regional sectoral studies (Franko et al. 2001, Messner and Geyler 2001) in which the development of individual economic sectors under the conditions of the various scenarios had been worked out.

From an ecological viewpoint, the main effects to be expected by the relevant land use changes in the Torgau case study were changes in the water balance and in the level of groundwater nitrate pollution. The hydrological effects were simulated with a hydrological-ecological runoff model (ABIMO), which was used to model data for natural groundwater recharge (Volk et al. 2001). This was then taken as a basis in conjunction with area-related nutrient balances to estimate nitrogen discharge (Franko et al. 2001). The ecological effects of gravel mining were estimated by experts on the basis of existent ecological maps (Bruns et al. 2001).

Regarding the modeling, estimation and the scenario effects, extensive sensitivity analyses were carried out. As a result not only point estimates for the criteria values were generated but also probability distributions reflecting various kinds of data and model uncertainties (see Sec. 5).

3.4 Step 4: Monocriteria and multicriteria assessment

The fourth step can be divided into two parts: monocriteria and multicriteria assessment. The monocriteria assessment evaluates the alternatives with respect to each single criterion selected in step 2. The multicriteria assessment aggregates the monocriteria assessments into a final recommendation.[5] This subsection concentrates on monocriteria assessment. How the subsequent multicriteria assessment works and how it was applied in the Torgau case study is explained in the Sections 4 and 5.

The common approach of economic decision aid, i.e. benefit-cost analysis, is to assess all the effects of the alternatives under investigation by one criterion. This makes all the effects comparable and enables a complete ranking of the alternatives. Benefit-cost analysis suffers from several methodological weaknesses, chiefly (see Hanley and Spash 1993, Månsson 1999):

- practical problems of monetarizing environmental, social and macroeconomic effects,
- inappropriate consideration of irreversibility and long term effects, and
- the exclusive focus on efficiency in order to measure welfare.

[5] However, the latter need not consist of a complete ranking of the alternatives.

As a rationale of assessment, it was required to evaluate as many effects as possible in welfare terms – as far as monetary evaluation is feasible, makes sense, and is based on reliable data. In the case study indirect methods of monetarization were exclusively used (Messner and Geyler 2001).

All the effects that could not be evaluated by means of benefit-cost analysis were to be assessed by the additional criteria being defined and derived in Step 2. Some of these additional assessments seem to be less complicated then benefit-cost analysis at first glance. For example, input-output analysis directly provides the values for the economic criterion ‘gross value added’ and the social criterion ‘employment’. Since the easy assessment rule ‘the more the better’ is valid, the actual monocriteria assessment in these instances takes place implicitly with the modeling. Monocriteria assessment was more sophisticated regarding ecological criteria. Choosing the nitrate concentration in the percolation water as a criterion was a first assessment step. The modeling, however, produced data on the spatial distribution of nitrate concentrations such that aggregation over space was a compulsory assessment step. The assessment of the ecological impacts of gravel mining was done by means of risk assessment referring to the objects of protection defined by the natural protection law (Bruns et al. 2001). The result was a classification of the alternatives into ‘good’, ‘mean’ and ‘bad’.

4 Multicriteria analysis

At first we discuss why we chose PROMETHEE as the multicriteria method to be applied in the case study. To understand how PROMETHEE is extended for uncertainty in Sec. 5 it is necessary to explain the concept of preference function (Sec. 4.2) as well as PROMETHEE under the assumption of certainty (Sec. 4.3).

4.1 Different monocriteria and multicriteria approaches

In contrast to benefit-cost analysis, multicriteria analysis allows for measuring the performance of an alternative by various criteria using different units. In planning sciences, operations research and increasingly also economics, multicriteria analysis[6] is considered an adequate

[6] We concentrate on the so-called multi-attribute decision methods (MADM) which assumes a finite number of alternatives to be compared, in contrast to the methods of multi-objective decision analysis (MODM) which assume a continuous decision space.

tool to aid public and private decision-making (e.g. Bana e Costa 1990: Chap. 5, Vincke 1992, Munda 1995, Roy 1996, Beinat and Nijkamp 1998). Welfare can be integrated by treating it as one criterion of many.

Several methods of multicriteria analysis are available. Stewart (1992), Vincke (1992), and Roy (1996) distinguish between:

1. utility-based methods such as the multi-attribute utility theory (MAUT) (Keeney and Raiffa 1976) and the analytical hierarchy process (AHP) (Saaty 1980),[7]
2. interactive methods like the step method (STEM) (Benayoun et al. 1971) and interactive multiple goal programming (IMGP) (Spronk 1981), and
3. outranking methods such as ELECTRE (Roy 1968), PROMETHEE (Brans and Vincke 1985, Brans and Mareschal 1990) and NAIADE (e.g. Munda 1995).

To analyze the above-described problem for public decision-making, either a utility-based method or an outranking method appears to be most appropriate. Outranking methods are characterized by the fact that the overall ranking of the alternatives is ultimately based on a pairwise comparison of the alternatives with respect to each criterion using pairwise preferences. The main difference between outranking methods on the one hand and MAUT as well as interactive methods on the other hand is that the latter assume the existence of an overall value, utility, that is to be maximized and governs all human decisions. Consequently, most of the work of a MAUT or interactive method analyst consists in extracting this utility function from the decision-maker's mind.

In outranking methods alternatives are always valued relative to other alternatives (using pairwise preferences). One consequence is that in outranking methods the inclusion of even a clearly dominated alternative may change the ranking of all the alternatives, which may be regarded as a disadvantage. On the other hand, the use of relative values is a – for our purpose decisive – advantage in the consideration of model uncertainty, as will be seen below in Section 5.3.

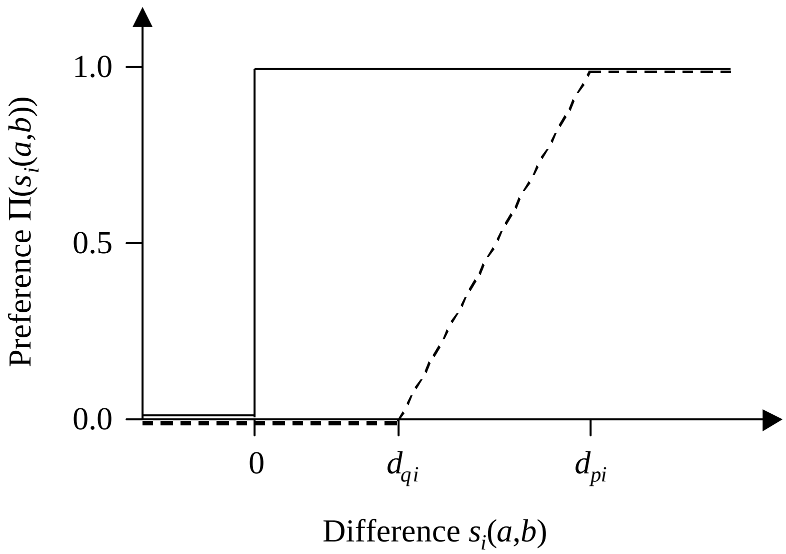
[7] In contrast to MAUT, in the AHP there may be a hierarchy of goals. Like MAUT, the AHP method makes use of a scalar value function to aggregate these goals and although being formulated only with regard to MAUT, our arguments below apply for AHP, as well.

4.2 Preference function

The concept of preference function to be explained below forms the basis of PROMETHEE.

Let A be the finite set of all alternative actions. The decision problem is to select the best action or – more extensively – to rank all alternatives. The performance of an alternative with respect to an objective of the decision-maker is measured by a criterion. Formally, a criterion i is a function $g_i : A \to \mathbb{R}$, taking its value in the totally ordered set $\mathbb{R}$, and representing the decision-maker's preferences according to some point of view (Vincke 1992: 27). A central step in all outranking methods is the pairwise comparison of alternatives by a preference function. A (partial) preference function is a function $\Pi_i : A \times A \to [0,1]$. The quantity $\Pi_i(a,b) \equiv \Pi(s_i(a,b))$ is a function of the difference $s_i(a,b) = g_i(a) - g_i(b)$ between the performances of alternatives a and b in criterion i. A value of $\Pi_i(a,b) = 1$ represents strict preference of a over b in criterion i, a value of 0 represents indifference or a preference of b over a. Figure 2 shows two common forms of the (partial) preference function.

Figure 1: Preference of an alternative a over an alternative b in a criterion i as a function of the difference between the values ($s_i(a,b) = g_i(a) - g_i(b)$).



Solid line: normal preference;
Dashed line: preference with indifference and weak preference (indifference threshold d_{qi} and preference threshold d_{pi}: see text).

The form in solid lines is called 'normal preference function' and assumes that alternative a is strictly preferred (indifferent) to alternative b in criterion i if $g_i(a)$ is greater than (equal to) $g_i(b)$. The form in dashed lines acknowledges that people are not always willing or able to strictly decide whether alternative a is better than b in criterion i, even if $s_i(a,b) > 0$. In this case a is strictly preferred to b only if its performance g_i exceeds that of b by a quantity d_{Pi} which is called a preference threshold. There is indifference between two alternatives a and b if $s_i(a,b)$ is below an indifference threshold d_{qi}. If $s_i(a,b)$ lies between the two thresholds, $d_{qi} < s_i(a,b) < d_{pi}$, then there is hesitation between strict preference and indifference called weak preference (Vincke 1992: 74).[8]

The total pairwise preference $\Pi(a,b)$ of an alternative a over an alternative b is the weighted sum[9] of partial pairwise preferences:

$$\Pi(a,b) = \sum_i w_i \Pi_i(a,b) \tag{1}$$

4.3 PROMETHEE

Several ways exist to deduce a rank order from the pairwise preferences Π, which lead to different outranking methods, such as ELECTRE (Roy 1968), NAIADE (Munda 1995) and PROMETHEE. In contrast to other outranking methods, PROMETHEE has the advantage that the concepts and parameters involved have some physical or economic interpretation easily understandable by the decision-makers (Vincke 1992: 73). The simplicity of PROMETHEE makes it easy to integrate uncertainty. PROMETHEE is, due to the pairwise comparisons, restricted to discrete decisions, i.e. only a finite number of alternatives can be ranked.

One important common feature of all outranking methods is that the rank orders they produce are not necessarily complete but may be partial (pre)orders, meaning it is not always possible for all pairs of alternatives to decide whether the first alternative is ranked higher, lower or equal to that of the second alternative. This can be seen very simply in the PROMETHEE method, which acknowledges that there are (at least) two possible ways to

[8] Even if the consequences of the alternatives are certain, the decision makers might hesitate to decide between indifference and strict preference of one alternative with respect to a certain criterion if there are additional criteria. For instance a price difference of 100 Euro for a car seems to be irrelevant if the buyer is also concerned about the design, equipment, fuel consumption etc.

[9] The importance of the weights is discussed in detail in Sec. 5.4.

create a complete rank order of alternatives in a set A of all alternative actions. The rank of an alternative $a \in A$ could be measured by the sum of the pairwise preferences of this alternative over all the alternatives in the set A:

$$\Phi^+(a) = \sum_{x \in A} \Pi(a, x) \tag{2}$$

where a is preferred to b if $\Phi^+(a) > \Phi^+(b)$. Alternatively the rank of A could be measured by the sum of the preferences of the other alternatives in the set A over a:

$$\Phi^-(a) = \sum_{x \in A} \Pi(x, a) \tag{3}$$

where a is preferred to b if $\Phi^-(a) < \Phi^-(b)$. If weak preference exists in some of the criteria, i.e. if some of the thresholds p_i and q_i are nonzero, then the sum $\Pi(a,b) + \Pi(b,a)$ is not a constant for all pairs of alternatives (a,b) and thus $\Phi^+(a) > \Phi^+(b)$ does not imply $\Phi^-(a) < \Phi^-(b)$.

Now PROMETHEE combines both measures and defines:

- a preferred to b if $\Phi^+(a) > \Phi^+(b)$ and $\Phi^-(a) < \Phi^-(b)$;
- b preferred to a if $\Phi^+(a) < \Phi^+(b)$ and $\Phi^-(a) > \Phi^-(b)$;
- a and b are indifferent if $\Phi^+(a) = \Phi^+(b)$ and $\Phi^-(a) = \Phi^-(b)$;
- a and b are incomparable otherwise.[10]

Consequently, if there are weak preferences in one or more criteria incomparability can occur and lead to a partial rank order.[11]

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[10] There exist different variations of PROMETHEE: The described definition of the preference, indifference and incomparability relations are called PROMETHEE I. In contrast to this version in PROMETHEE II it is $\Phi(a,b) = \Phi^+(a,b) - \Phi^-(a,b)$ and a is preferred to b iff $\Phi(a,b) > 0$. In PROMETHEE II the result is always a complete rank order of the alternatives.

[11] If only normal preferences are used in PROMETHEE the intensity of preferences have no impact on the ranking of the alternatives. This is – at least to a certain degree – not the case if weak preferences are applied.

5 Extending decision support methods for uncertainty

5.1 Types of uncertainty and ignorance

In order to discuss how IANUS is able to deal with uncertainty it is important to distinguish between different forms of uncertainty. Throughout this article we use uncertainty as a generic term for all kinds of 'being not certain". According to Knight (1921) in an uncertain decision situation one can distinguish between risk and uncertainty (sensu strictu). There is risk if the decision-maker knows all the possible events and their probabilities. Knight calls a situation uncertain (sensu strictu) if the decision-maker only knows the set of possible events but not (all of) their probabilities. Faber and Proops (1997: 113) supplement this distinction by a third category – ignorance. Ignorance occurs if in contrast to risk and uncertainty situations the set of all possible events is not completely known.[12]

This classification is not completely selective. However, it is useful to explain how IANUS approaches uncertainty. In general, a decision situation is characterized by ignorance. A thorough analysis can reduce ignorance. In the IANUS approach (as well as in many other decision-support methods), modeling is extensively used to improve knowledge about the decision's effects.

A strategy widely used to deal with ignorance – including in this paper – is to subsequently treat it as if it were a risk situation. This is done by assuming in a first step that all essential effects of the alternative actions can be anticipated. This assumption is justified by the argument that unknown effects cannot be included in the analysis. The decision problem can be further simplified to a risk situation by the usage of subjective probabilities if objective probabilities are unavailable. In contrast to objective probabilities derived for instance from natural laws (e.g. tossing a fair coin), subjective probabilities reflect the beliefs of individuals. Therefore they generally differ from person to person. In the case of a single decision-maker, the strategy would be to use his subjective probabilities for a further analysis. But if there is a group of decision-makers the identification of probabilities may cause serious problems.

In the literature, three types of uncertainty are formally discussed within the framework of multicriteria analysis: development uncertainty, model uncertainty (e.g. D'Avignon/Vincke

[12] Faber and Proops further refine their classification. For our purpose this coarse distinction is sufficient. In the economics literature there exist several other classifications of uncertainty (e.g. Ravetz 1986, Funtowicz/Ravetz 1991, Perrings 1991).

1988, Zimmermann 1986, 1990, Bouyssou 1990, Munda 1995) and weight uncertainty (e.g. Bana e Costa 1990, Janssen et al. 1990). The following sections are devoted to describing these types in more detail and outlining how they are included in the IANUS method.

5.2 Development uncertainty

Development uncertainty arises if the decision depends on assumptions concerning the future and so the values of the multicriteria matrix depend on some external factors describing the future development of the system or region considered. As these are uncertain, the values of the multicriteria matrix are uncertain as well. Technically, this development uncertainty may be regarded as a form of data uncertainty. However, it makes sense to distinguish between the many small sources leading to uncertain data, such as variability in soil or ground water conditions and data measurement failures, and the large few dominating external factors, such as climate change or economic growth. IANUS deals with the latter form of uncertainty by distinguishing several frameworks of development and using them as variable descriptions of more or less likely external circumstances for the evaluation process.

There are two ways of dealing with development uncertainty within multicriteria analysis. First, a complete analysis for each developmental framework can be performed and the results compared visually. Second, the multicriteria matrices for the various developmental frameworks can be aggregated. For this a likelihood p_k for each development framework $k = 1,...,K$ is estimated. Then the preference of an alternative *a* over an alternative *b*, considering all frameworks of development, is the weighted sum

$$\Pi_{tot}(a,b) = \sum_k p_k \Pi_{tot}^k(a,b) \tag{4}$$

where $\Pi_{tot}^k(a,b)$ is the pairwise preference of *a* over *b* in framework *k* (cf. Eq. 1).

In the case study of the Torgau region, the probabilities attached to the framework of development were calculated based on assumptions on the subjective probabilities of the development of the issues mentioned in Footnote 5. The resulting probabilities are REALO 60 %, STAGNATION 35 % and BOOM 15 %.

5.3 Model uncertainty

Model uncertainty occurs when the input data of the model used to predict the effects of the alternatives are uncertain or if the model itself is not accurate. In the following we describe an extension of PROMETHEE that takes model uncertainty into account.[13] This is basically done by adjusting the preference functions $\Pi_i(a,b)$ to uncertainty. Let us assume for the moment that all preference functions are normal (see Fig. 1). Thresholds and weak preferences are discussed at the end of this subsection.

Figure 2: Probabilistic distributions of the performances $g_i(a)$ and $g_i(b)$ of two alternatives a and b. The scales of $g_i(a)$ and $g_i(b)$ are arbitrary.

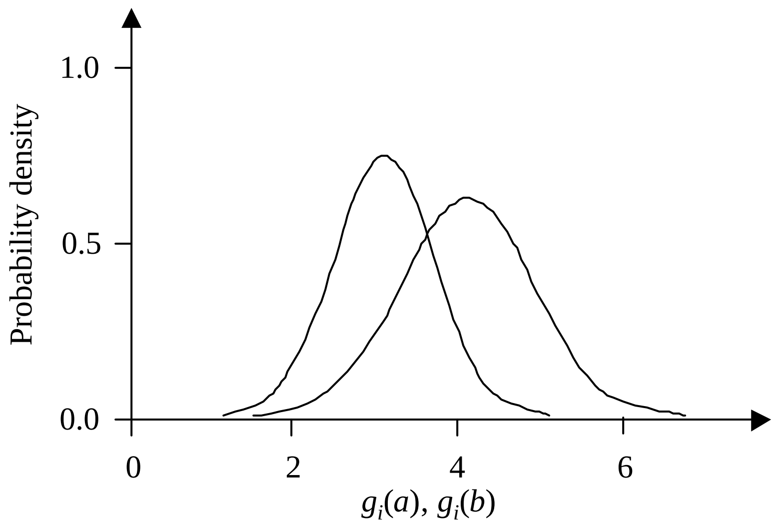


Figure 2 shows the uncertain performances $g_i(a)$ and $g_i(b)$ of two alternatives, *a* and *b*, in a criterion *i*, described by probability distributions. If the uncertainty in the performances of the alternatives is large, it becomes difficult to clearly decide which of the two alternatives is superior with respect to criterion *i* and by how much. The basic rationale in the probabilistic comparison of two alternatives is, the smaller the overlap between the two membership functions, the larger the preference for the superior alternative. Based on this idea, a straightforward way of calculating the preference of *a* over *b* is to relate it to the probability that alter-

[13] Uncertainty is usually considered either by fuzzy set approaches (Zimmermann 1986, 1990, Munda 1995) or by probabilistic approaches (D'Avignon/Vincke 1988, Bouyssou 1990). Even though the conceptual basis of fuzzy set theory and probability theory differ, in practice there are strong similarities between the two approaches within the framework of multicriteria analysis.

native *a* performs better than alternative *b*, i.e. $P(g_i(a) > g_i(b))$. But four plausible requirements should be met by a stochastic preference function:

1. If $P(g_i(a) > g_i(b)) = 1$ we are sure that *a* performs better than *b* in criterion *i* and decide on strict preference: $\Pi_i^{(s)}(a,b) = 1$ (the letter *s* stands for 'stochastic" to distinguish this 'stochastic preference function" $\Pi_i^{(s)}(a,b)$ from the preference functions discussed in Sec. 4.2).

2. If $P(g_i(a) > g_i(b)) = P(g_i(b) > g_i(a)) = 0.5$ then the observation of *a* outperforming *b* is as likely as the observation of *b* outperforming *a*, and there should be indifference between *a* and *b*: $\Pi_i^{(s)}(a,b) = 0$.

3. For intermediate probabilities, i.e. if $0.5 < P(g_i(a) > g_i(b)) < 1$ the preference should satisfy $0 < \Pi_i^{(s)}(a,b) < 1$.

4. For small probabilities $P(g_i(a) > g_i(b)) < 0.5$ the observation of *a* outperforming *b* is less likely than the observation of *b* outperforming *a* and it should apply that *a* is not preferred to *b*: $\Pi_i^{(s)}(a,b) = 0$.

These requirements are fulfilled by the following formula for the stochastic preference function:

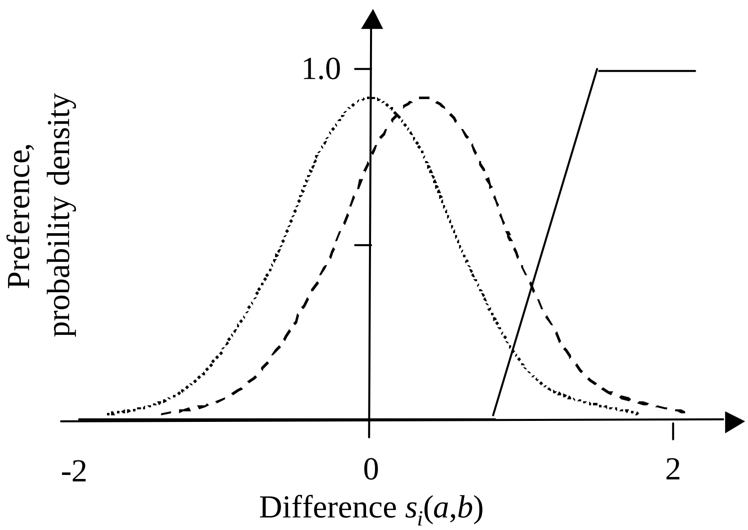
$$\Pi_i^{(s)}(a,b) = \max\{0, P(g_i(a) > g_i(b)) - P(g_i(b) > g_i(a))\} \tag{5}$$

One issue that is often overlooked is that uncertain quantities may be correlated. In the Torgau study, for example, much of the variation in the nitrate concentration is caused by the unknown rainfall. This uncertainty, however, affects all alternatives in the same way. Hence if an alternative *a* is better than an alternative *b* under a high rainfall condition, it is also better under a low rainfall condition. Consequently, $P(g_i(a) > g_i(b)) = 1$ and despite the uncertainty, *a* is strictly preferred to *b*. The reason for this is that the uncertainty in the g_i is perfectly correlated between the alternatives *a* and *b*. If in contrast most of the uncertainty in $g_i(a)$ was caused by factors that are not correlated with those factors that cause most of the uncertainty in $g_i(b)$ (and provided there is some overlap between the two probability distributions, as in Fig. 2), there would be a non-zero probability that $g_i(b) > g_i(a)$. Consequently, $P(g_i(a) > g_i(b)) < 1$.

To capture these correlations, it is not sufficient to know for each alternative $a \in A$ the corresponding probability distributions of the performances $g_i(a)$. What is needed for all pairs of alternatives $(a,b) \in A \times A$ are the probability distributions of the *differences between the performances* of the alternatives, i.e. the probability distributions of $\{g_i(a) - g_i(b)\}$. One example of such a probability distribution of differences between two alternatives a and b is shown in Fig. 3 (dashed line). The probability $P(g_i(a) > g_i(b))$ is given by:

$$P(g_i(a) > g_i(b)) = \int_0^\infty p(s_i(a,b))\, ds_i(a,b) \quad \text{with} \quad s_i(a,b) = g_i(a) - g_i(b) \tag{6}$$

Figure 3: Combination of uncertainty and preference function.



Dashed line: first example of a probability density $p(s_i(a,b))$;
Dotted line: second example of a probability density $p(s_i(a,b))$;
Solid lines: example of a preference function $\Pi_i(s_i(a,b))$

In Eqs. (5) and (6) we assumed a normal preference function. In other words, each positive difference $s_i(a,b)$ leads to a strict preference $\Pi(s_i(a,b)) = 1$. To generalize Eq. (6) for arbitrary preference functions, $\Pi(s_i(a,b))$ (e.g. the one in Fig. 3, solid line), we use the fact that both Eq. (6) and the preference function only depend on the difference $s_i(a,b)$ and write:

$$\tilde{\Pi}(g_i(a) > g_i(b)) = \int_0^\infty p(s_i(a,b))\Pi(s_i(a,b))\, ds_i(a,b) \tag{7}$$

Equation (7) can be interpreted in two ways. First, one can say that for each difference $s_i(a,b)$ the probability density $p(s_i(a,b))$ is taken and weighted by the preference $\Pi(s_i(a,b))$. These weighted probability densities are formed for all $s_i(a,b) > 0$ and summed up to yield a 'modified' probability $\tilde{\Pi}(g_i(a) > g_i(b))$ that is roughly speaking the probability $P(g_i(a) > g_i(b))$ weighted by the preference function $\Pi_i(a,b)$. Alternatively, and mathematically more precisely, Eq. (7) is the average of the preference function $\Pi(s_i(a,b))$ taken over all positive $s_i(a,b)$ weighted by probability density function $p(s_i(a,b))$. Then $\tilde{\Pi}(g_i(a) > g_i(b))$ has the meaning of an average preference.

However, $\tilde{\Pi}(g_i(a) > g_i(b))$ does not meet the Requirement 2 for stochastic preference functions (see above). To see this, imagine for instance a probability density function that is symmetrical where positive and negative $s_i(a,b)$ are equally likely (cf. dotted line in Fig. 3). Here $\tilde{\Pi}(g_i(a) > g_i(b))$ would be positive – running against Requirement 2, which calls for indifference in such a case. Instead, the appropriate preference function is the analogue of Eq. (5):

$$\Pi_i^{(c)}(a,b) = \max\{0, \tilde{\Pi}(g_i(a) > g_i(b)) - \tilde{\Pi}(g_i(b) > g_i(a))\} \tag{8}$$

where the letter *c* stands for 'combined' and means that now the preference includes both the uncertainty in the g_i and the preference function $\Pi_i(a,b)$. To check consistency, for a normal preference function in the case of uncertainty, Eq. (8) is identical to Eq. (5) while in the case of certainty it reproduces the preference function $\Pi_i(a,b)$ from Sec. 4.2. To incorporate this combined preference into the framework of PROMETHEE, we replace the $\Pi_i(a,b)$ by $\Pi_i^{(c)}(a,b)$ in Eqs. (1)-(3).

5.4 Weight uncertainty

The outcome of the multicriteria analysis depends to quite some extent on the values of the weights w_i, which reflect the belief of the decision-maker about the relative importance of the criteria. The selection of weightings is hence an important preliminary decision which has to be taken by decision-makers – if necessary with the assistance of decision analysts. If the decision-makers are unable to attach weights to the criteria, we call this phenomenon weight uncertainty. One reason for this might be that the decision-makers are just not certain about the importance of the criteria. In public decision processes where a large number of people is involved or concerned, another reason might be that the weights differ among the decision-makers and that it is therefore practically difficult to elicit all the weights precisely.[14] A third reason could be that the interest of stakeholders should be taken into consideration. Normally, neither the decision-makers nor the stakeholders know their beliefs regarding the importance of the criteria.

Therefore, a procedure was developed and applied in the Torgau case study that moves from a non-normative and explorative analysis to a normative one.[15]

1. In a first explorative step the weights are not fixed; instead a large number (1,000) of weight combinations is drawn randomly.[16] For each weight combination the PROMETHEE method is performed and a rank order of the alternatives determined. Then for each alternative the frequencies of the alternative being on rank 1, rank 2, etc. is calculated. If, for example, one alternative is very often in first place, it is likely to satisfy many people – and so this step is able to assess the general acceptance of an alternative.

2. In the second step, the variability in the weights is partly restricted by fixing the ratios of some of the weights. For this the criteria are organized into groups. In the case study of the Torgau region, one group contained the ecological criteria, another the social and a third the economic criteria. Usually it is easier to fix the weights within individual groups. In Torgau it was assumed that the net benefits (reflecting the welfare) should weigh twice as much as the gross added value (taken as an indicator of the economic power of the region). The ratio between the ecological criteria 'nitrate concentration' and environmental impact assessment was set at 9:1. The group of social criteria contained only employment. The relative weights of the whole groups, which allow the discussion of the big trade offs between ecological, social and economic values, are still kept variable. As in the first step they are drawn randomly and the probabilities of an alternative *a* being on a rank *r* are

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[14] The latter cause is not uncertainty in a rigorous sense since it is assumed that each decision-maker is certain about his weighting. However, from the point of view of a decision analyst the reasons for the inability of determining the weights are of secondary interest.

[15] Other approaches to deal with weight uncertainty were developed by Bana e Costa (1990a) and Janssen et al. (1990).

[16] The weights were drawn randomly in a way that the mean weight was the same for each criteria. Of course this assumption can be changed if there are good reasons for an unbalanced probability distribution.

determined. As the weights are partly fixed in this step, it is partly normative and partly explorative.

3. In the last step all weights are fixed and we have arrived at a completely normative analysis. In the Torgau case it was decided that the groups of economic, social and ecological criteria are of the same importance – reflecting an aspect of sustainable development. The resulting weights were:

   - *economic criteria:* net-benefits $1/3 \times 2/3 = 0.22\overline{2}$, value added $1/3 \times 1/3 = 0.11\overline{1}$;
   - *social criterion:* employment $0.33\overline{3}$;
   - *ecological criteria:* nitrate concentration $1/3 \times 9/10 = 0.3$, environmental impact assessment $1/3 \times 1/9 = 0.03\overline{3}$.

6 Results of IANUS in the Torgau Region

The monocriteria assessments of the different scenarios for the case study are aggregated over all three frameworks of development by calculating their expected value, i.e. their sum weighted by their probabilities.[17] The result is a multicriteria matrix which shows for each alternative its performance with regard to the five criteria (Table 2).

Considering the ranks of the scenarios with respect to each evaluation criterion it becomes apparent that the results are heterogeneous, i.e. the scenario rankings differ between the criteria. Even comparison of the economic and social criteria (net benefit, value added, and employees) reveals large deviations. These trade-offs between the ranking of different criteria clarify that a multicriteria assessment is necessary in order to attain an overall scenario ranking.

[17] Of course, it is also possible to analyse the three frameworks of development separately (see Messner, Drechler et al. 2001: 294-299).

*Table 2: Multicriteria matrix aggregated over all frameworks of developments **

Criteria / Alternatives (A)	Net benefit undiscounted (difference with regard to A_1)		Value added (difference with regard to A_1)		Employees (difference with regard to A_1)		Nitrate concentration (mean value)		Ecological assessment of gravel mining	
	[Mio. DM]	Rank	[Mio. DM]	Rank	[Person years]	Rank	[mg/l]	Rank	Assess-men classes	Rank
A_1: wpz= gravel+	0	*3*	0	*3*	0	*1*	78	*1*	Mean	*3*
A_2: wpz– gravel+	–7.5	*4*	14.8	*1*	–88.1	*3*	94	*3*	Bad	*4*
A_3: wpz= gravel=	5.9	*1*	–7.6	*4*	–39.9	*2*	78	*1*	Good	*1*
A_4: wpz– gravel=	4.9	*1*	9.5	*2*	–128.3	*4*	94	*3*	Good	*1*

wpz = / – no changes (=) or reductions (–) in the size of the wellhead protection zones (wpz)
gravel+ / = opening of new gravel pits (+) or no further openings (=)

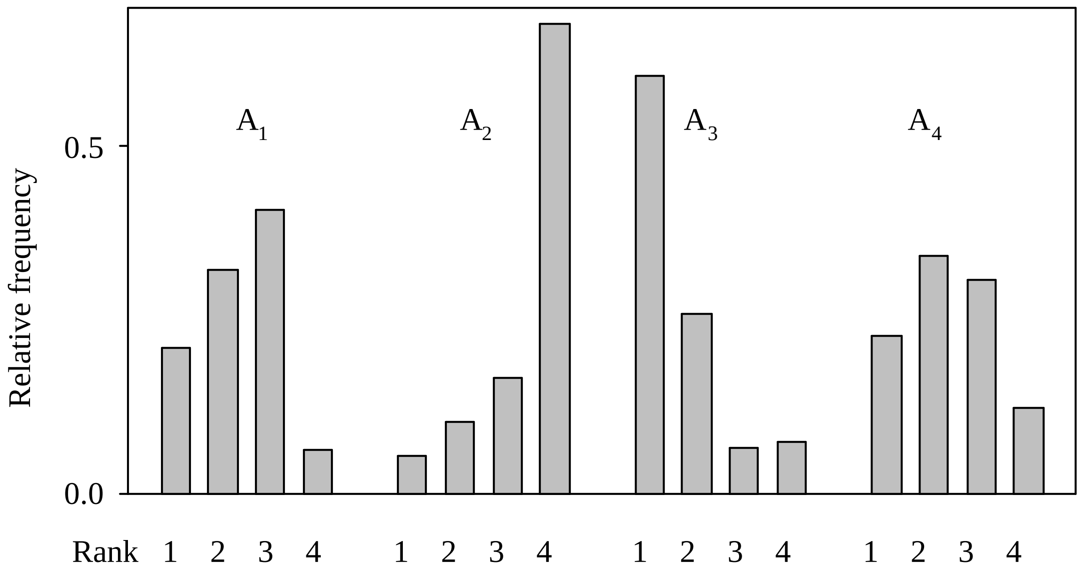
* Regarding the ranks in the table, indifference and preference thresholds (cf. Sec. 4.2) were introduced for each criterion. The indifference threshold values are DM1 million for net benefit, DM2 million for value added, 10 person years for employees, 1 mg/litre for nitrate concentration. The preference threshold values are DM5 million, DM10 million and 5 mg/l, respectively.

Source: Messner, Drechsler et al. 2001, p. 306.

Let us take a closer look on some of the figures in Table 2. The first column tells us that additional gravel mining has adverse welfare effects. The main reason for this is that additional gravel production is not likely to be very profitable due to a stagnation and low gravel prices that already can be observed in the German construction and gravel markets for several years. . Regarding value added and nitrate concentration we remark that a reduction of the wellhead protection zones leads to a more profitable agriculture, but also to increased negative ecological effects. Comparing the results for the criteria value added and employees reveals that a reduction of the protection zones has a positive effect on the economic performance of the region but not on employment. The rationale behind this is that agriculture within wellhead protection zones is compelled to additional, labor-intensive measures.

Based upon the application of the extended PROMETHEE method as described above, Figure 4 shows the result for the first step of weighting (analysis of a thousand randomly selected weight combinations).

Figure 4: Relative frequency of the alternatives´ rankings
(with aggregation of frameworks of development and with data uncertainty).



The third alternative is located with an outstanding frequency on the first two ranks while alternative 2 is very frequently positioned on the last rank. Alternative 1 seems to be preferred to Alternative 4 if one looks at the avoidance of rank 4, but both alternatives cannot be discriminated clearly. Thus, this first tentative analysis with random weights tends to indicate the following ranking of alternatives: 3, 1/4, 2. However, a final assessment of the ranking must be left to the decision-maker.

Amazingly, these results were largely confirmed in steps 2 and 3 of the multicriteria analysis with normative weights (results not shown explicitly here). Only Alternative 1 performs increasingly better than Alternative 4. Furthermore, it became evident that in the case study the inclusion of uncertainty variations in the data did not have an impact on the resulting rankings. Thus, the result can be labeled as robust.[18]

From a methodological point of view these results indicate for the case of Torgau:

[18] For a detailed description of the method, the assumptions and the results, including a separate analysis for all three frameworks of development, cf. Drechsler 2001 and Messner, Drechsler et al. 2001.

- Despite the heterogeneity in the data of the multicriteria matrix, the extended PROMETHEE method can produce clear findings.
- Compared to the results of the benefit-cost analysis (column 1 in table 1), the multicriteria analysis resulted in a similar but a much more clear-cut scenario ranking.
- The inclusion of different types of uncertainty did not change the ranking.
- The first explorative analysis with randomly selected weights already produced results that were confirmed in later stages of the analysis.

With regard to the conflict situation in the Torgau region, the results indicate the following:

- Alternatives 3 and 1, which after the multicriteria analysis are on the first two ranks, contain no reduction of wellhead protection zones. Considering Table 1, it can be seen that many economic, social and ecological criteria support those two alternatives – the only exception being the value added criterion. Thus, our recommendation regarding this dispute is straightforward: the wellhead zones in the Torgau region should not be reduced.
- Furthermore, one of the major arguments in favor of wellhead protection zone reductions reads that welfare effects from the gravel mining sector are prevented by the retention of the zones. This could not be confirmed. On the contrary, alternatives 1 and 2 with additional gravel mining were revealed to be less welfare-increasing than alternatives 3 and 4 without additional gravel mining (cf. table 2, column 2, net benefit). Two major arguments underpin this result. First, large gravel production over-capacities exist in eastern Germany while gravel demand is stagnant – therefore gravel mining in the Torgau region is not likely to be very profitable in the years to come. Second, it was revealed in the study that mining pits inside well head protection zones with thick gravel layers are not necessarily more profitable than those outside, because the latter sometimes show a larger gravel fraction.

7 Outlook

IANUS is an integrated method for the support of public decision-making based on a multicriteria approach. The method has been developed for a problem that was characterized by conflicting claims on land use and by trade-offs between the protection of natural resources and economic development. It proved to be an appropriate method for the analysis of conflicts over water management. It is a methodological approach for a problem originated in the actual practice of public decision-making. But the scope of problems to be analyzed with IANUS is very broad. It can be applied to any kind of usage conflicts between natural resources and economic development on different spatial scales. The method helps sound decisions to be made which take responsibility for the environment, fellow humans as well as future generations. Therefore, it is a tool which contributes to sustainable development.

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