Available online at www.sciencedirect.com

SCIENCE DIRECT®

European Journal of Operational Research 162 (2005) 418–432

EUROPEAN JOURNAL OF OPERATIONAL RESEARCH

www.elsevier.com/locate/dsw

Stochastics and Statistics

Identification of a small reliable and efficient set of consistent scenarios

Olaf Tietje *

Systaim—Aim-Oriented Decision Support for Sustainable Systems, An ETH Zürich Spin-Off, o.tietje.Systaim GmbH,
Friedheimstr. 17, CH 8057 Zürich, Switzerland

Received 10 June 2002; accepted 21 August 2003
Available online 11 December 2003

Abstract

In scenario analyses, in which experts have rated the consistency of impact factor levels, all scenarios are defined by vectors of these impact factors. Because the identification of scenarios out of all combinatorial scenarios was time consuming and inefficient, three new approaches were developed: Local efficiency as a goal function of a simple combinatorial optimisation, a multidimensional distance indicator for sets, and a small and efficient selection algorithm. The methods are illustrated and tested on a large scenario analysis from an ETH-UNS case study. Their convergent validity is shown by the comparison of the selected scenarios.

Keywords: Scenarios; Formative scenario analysis; Consistency analysis; Convergent validity; Combinatorial optimisation

1. Introduction

Starting with the famous book of Kahn and Wiener (1967) scenario analysis became a major decision tool, e.g. in management, economics, and environmental decision-making (see, MacNulty, 1977; Cooke, 1991; Heugens and van Oosterhout, 2001; Scholz and Tietje, 2002). The drawbacks of deterministic forecasting models (be it environmental, economic or ecological models), that they typically only yield a single prediction and do not include qualitative system changes ("disruptions", Godet, 1986) made the idea appealing to identify a small number of scenarios, which represent different possible future states of a system. The reasoning behind this is that—based on a reliable scenario analysis—the reality can be reperceived, individual engagement, commitment, and mental flexibility can be enhanced (Heugens and van Oosterhout, 2001), and best reply strategies (Scholz and Tietje, 2002) can be developed.

Scenario analysis spread into many disciplines and even into common language (Collins, 1995). Unfortunately the term scenario analysis was often mixed up with sensitivity analysis or with just the variation of a model parameter or even with forecasting (as already noted by Godet, 1986). At the same time the development of formal scientific procedures of scenario analysis (Götze, 1993;

---

* Tel.: +41-43-534-6730.
E-mail address: olaf.tietje@systaim.ch (O. Tietje).
URL: http://www.systaim.ch.

0377-2217/$ - see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/j.ejor.2003.08.054

Missler-Behr, 1993; Scholz and Tietje, 2002) has often been disregarded and ignored—not only within environmental sciences.

From a mathematical point of view scenario analyses can be divided into three different types: holistic scenarios, model scenarios, and formative scenarios. A *holistic scenario analysis* develops scenarios by a number of experts in the required disciplines. Although qualitative narratives are essential for a scenario analysis in general (Heugens and van Oosterhout, 2001), qualitative and quantitative aspects of the scenarios may be included and both, intuition and formal analysis of experts, are combined (see, e.g., Kahn and Wiener, 1967). Mathematical methods (such as trend analysis and other statistics) and real-life experiments inspired by corporate strategies (in "non-cartesian" scenarios, Heugens and van Oosterhout, 2001) can be used to assess certain aspects of the scenarios. A *model scenario analysis* explicitly uses a (not always dynamic) system model, such as an economic or environmental model (see, e.g., Bossel, 1998; Ruth and Hannon, 1997). The systematic variation of the unknown or uncertain parameters in the model creates a number of trajectories, some of which the model experts select as scenarios to characterize different possible futures (see, e.g., Meadows et al., 1974). A *formative scenario analysis* (Scholz and Tietje, 2002; Götze, 1993; Missler-Behr, 1993) is based on qualitatively assessed impact factors and expert-rated quantitative relations between them, such as MICMAC analysis (Godet, 1986), consistency analysis (Scholz and Tietje, 2002) or cross-impact analysis (Götze, 1993; Brauers and Weber, 1988; Graf, 2002). In this categorisation, 'formative' indicates the generic mathematical structure behind the scenarios (see below) which is combined with quantitative/qualitative expert assessments. In the *ETH-UNS Case Studies* scenario analysis is mostly used within this framework. The theory has recently be shown (in Scholz and Tietje (2002)) and practical examples can be found there and in other publications of the *ETH-UNS Case Studies* (see ETH-UNS, 2003).

This investigation supports the consistency analysis as a core part of a formative scenario analysis. Although not specifically addressed here this will as well help in scenario interpretation. Within consistency analysis a scenario is conceived of as a set of system variables (impact factors) each of which is allowed to take only a small number (two to five) of different levels. With a considerable number of impact factors the combinatorial set of scenarios may become very large. As a basis for the selection of few final scenarios, several indicators have been proposed, such as consistency numbers ('Konsistenzzahlen', von Reibnitz, 1992; Götze, 1993; Missler-Behr, 1993; Scholz and Tietje, 2002) and scenario probability (Götze, 1993; Brauers and Weber, 1988; Graf, 2002). Although the indicators drastically reduce the number of scenarios, it still is considerably large. Therefore, the reduced set of scenarios has to be analysed statistically, for example applying cluster analysis (Götze, 1993; Brauers and Weber, 1988; Scholz and Tietje, 2002). Because this is a complicated and time-consuming task, a scenario selection method would be desirable, which supports the quality of the scenario analysis (confer the discussions in Götze (1993) and Scholz and Tietje (2002)) and which yields

- *consistent* scenarios, because inconsistent scenarios draw no realistic image of the future (this criterion is inherent to this kind of scenario analysis and therefore mentioned by all authors)
- significantly *different* scenarios (Götze, 1993; Brauers and Weber, 1988; Scholz and Tietje, 2002), because a decision maker is interested in a set of principally possible cases, which he has to account for, and small differences between similar scenarios mostly are not relevant, even if these differences could be identified with enough certainty (which is in general not the case)
- a *small* number of scenarios, because human decision makers can hardly compare many qualitatively different scenarios (Heugens and van Oosterhout, 2001) and a large number of scenarios may indicate a large redundancy (i.e. scenarios are similar)
- a *reliable* set of scenarios, because the scenario analysis is considered poor if different scenario analysts arrive at different results (Hassler and Schärli, 1996); even worse, when they obtain

different scenarios as a result of the same scenario selection procedure
- *efficient* scenarios (i.e. the most consistent scenarios within a group of similar scenarios, note that a consistent scenario is not necessarily efficient), because they are the most relevant representatives (compare to internal stability, von Reibnitz, 1992, p. 52).

Clear and meaningful graphical visualizations support to validate the expert ratings of consistency, to improve and accelerate the scenario selection process, and to evaluate the final set of selected scenarios. The primary objective of this manuscript, though, is to derive formal mathematical criteria for the scenario selection and to present improved methods of scenario selection. Three procedures of scenario selection were developed, applied to a large scenario analysis and investigated, to which extent they facilitate the identification of a small reliable and efficient set of significantly different consistent scenarios.

2. Conditions for the scenario identification

2.1. Consistency assessment

A *Formative Scenario Analysis* (FSA) encompasses several steps to represent the necessary information (see Scholz and Tietje, 2002; Götze, 1993; Godet, 1986; Brauers and Weber, 1988; Graf, 2002), such as the (overall) system view, lists (e.g. of impact variables and their strengths and weaknesses), graphical and numeric presentations (e.g. MICMAC analysis and consistency analysis), and the qualitative discussion and interpretation (e.g. novelistic case description). In this approach scenarios are hypothetical visions into the future (Scholz and Tietje, 2002; for a recent review of scenario definitions see Heugens and van Oosterhout, 2001).

A scenario describes a possible future state of a system by means of *impact variables* (or *impact factors)*. For each of the n impact variables y_i, $i = 1, \dots, n$, very few (n_i, preferably two to five) possible different levels (in German: *Ausprägungen*) $y_i^1, \dots, y_i^{n_i}$ are defined ($n_i \geqslant 2$, $i = 1, \dots, n$). Please note that the number of levels may vary for different impact variables. Viewing an impact factor y_i as the set of its levels, the combinatorial set S of scenarios is the set product

$$S := y_1 \times y_2 \times \cdots \times y_n \tag{1}$$

of all levels of all n impact factors. The combinatorial number of scenarios is the product of all numbers n_i of levels. Hence a scenario S_k is constructed as a vector $S_k = (y_1^{m_1}, \dots, y_n^{m_n})$, specifying one level m_i of each impact variable.

The consistency of a scenario as a whole is estimated by assessing the consistency of the levels of all pairs of impact factors. The consistency is rated on a specific scale, the consistency indicator. Table 1 gives examples of such a scale (Scholz et al., 1999). Several authors (see, e.g., Scholz and Tietje, 2002; Götze, 1993; Brauers and Weber, 1988) gave examples for the consistency estimation. Further applications are presented in almost

Table 1
Example definition of consistency indicators (Scholz et al., 1999)

Additive consistency indicator c_{add}	Explanation	Multiplicative consistency indicator c_{mult}
−2	Inconsistent: The levels are inconsistent and cannot occur at the same time	0
−1	Hindering: The levels hinder each other, but its not impossible that they occur at the same time	0.5
0	Uncorrelated: The levels can occur independently, there is no direct relation between them	1
1	Supporting: The occurrence of one level supports the occurrence of the other	2
2	Inducing: The occurrence of a level induces the other	3

all ETH-UNS case studies (see ETH-UNS, 2003, for the corresponding products/books published).

After the consistency rating of all pairs of impact variables the ratings are summarized in the *consistency matrix*

$$C := c(y_i^{m_i}, y_j^{m_j})_{i,j=1,\ldots,n;m_i=1,\ldots,n_i;m_j=1,\ldots,n_j}, \tag{2}$$

where $y_i^{m_i}$ denotes the m_ith level of the ith impact variable, n_i the number of levels of the ith impact variable. For each scenario S_k the matrix C can be reduced to C^- by eliminating rows and columns of levels not contained in S_k. Because the consistency indicator is symmetric, the matrix C then—for each scenario S_k—reduces to a quadratic lower triangle matrix C^-. The overall consistency c^* of a scenario S_k can now be calculated additively as (Scholz and Tietje, 2002)

$$c^*_{\mathrm{add}}(S_k) = \sum_{i=2}^{n} \sum_{j=1}^{i-1} c_{\mathrm{add}}(y_i^{m_i}, y_j^{m_j}). \tag{3}$$

This is simply the sum of all (nonzero) coefficients of the reduced matrix C^-. Another consistency indicator is the average rate of the additive consistency, which equals the additive consistency divided by the constant $1/2n(n-1)$ (Götze, 1993). Other examples can be found in Missler-Behr (1993). In many applications within ETH-UNS Case Studies the multiplicative consistency has been applied

$$c^*_{\mathrm{mult}}(S_k) = \prod_{i=2}^{n} \prod_{j=1}^{i-1} c_{\mathrm{mult}}(y_i^{m_i}, y_j^{m_j}). \tag{4}$$

Please note that the consistency ratings for the additive and multiplicative consistencies are different. The multiplicative consistency requires all coefficients of the consistency matrix to be nonnegative (see Table 1).

When conducting a scenario analysis there are the same explanations for the different levels of the additive and multiplicative consistency indicator (see Table 1). Therefore only one consistency matrix C has to be compiled. Although it is not a requirement, practically this has always been the additive consistency matrix. The multiplicative consistency matrix is then derived from it by means of a simple transformation.

Two additional consistency indicators are useful for the assessment of the overall consistency c^* of a scenario S_k, namely the number of inconsistencies of a scenario

$$c^*_{\mathrm{inco}}(S_k) = \sum_{i=2}^{n} \sum_{j=1}^{i-1} \begin{cases} 1 & \text{if } c_{\mathrm{mult}}\left(y_i^{m_i}, y_j^{m_j}\right) = 0 \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

and the minimum consistency level of a scenario

$$c^*_{\mathrm{conL}}(S_k) = \min_{i,j \text{ with } i=2\ldots n, j=1\ldots i-1} \left\{c_{\mathrm{add}}\left(y_i^{m_i}, y_j^{m_j}\right)\right\}. \tag{6}$$

The additive consistency is compensating: a negative consistency rating might be compensated by several positive consistency ratings. The multiplicative consistency is excluding: a single inconsistency (multiplicative consistency indicator equals 0) within a scenario sets also the overall multiplicative consistency to zero. If the consistency matrix (Eq. (2)) could include a pair of levels, which were falsely assessed as inconsistent, the allowed number of inconsistencies can be set to a value above zero. If conversely only those scenarios shall be considered, in which a certain minimum consistency is maintained for all pairs of levels, then the required minimum consistency can be increased.

2.2. Scenario selection

After the consistency assessment, i.e. when the list of impact variables and their levels have been defined and the consistency matrix has been assessed, the overall procedure of scenario selection may start (for additional information and practical access see Tietje, 2003). First, the set of all possible scenarios S is filtered in order to subsequently consider only those scenarios, which match specific criteria. For example a maximum number of inconsistencies (Eq. (5)), such as zero (see, e.g. Götze, 1993) or one, or a minimum consistency level (Eq. (6)) is required. The filtering leads to a subset S^* of S (Eq. (1)), which might still consist of several hundreds or in some cases even thousands of combinatorial scenarios.

There are two main proposals to select a final set of scenarios out of S^*. The concept driven top down procedure to select a set of scenarios (Scholz and Tietje, 2002), for example, identifies the impact factor levels of predefined scenarios, such as *business as usual* or *eco-max* (the 'best' scenario from an ecological perspective, Scholz et al., 1995). This incorporates qualitative considerations. The only quantitative data driven bottom up procedure proposed is investigating the filtered set S^* with a cluster analysis (e.g., Götze, 1993). Unfortunately this does not give a good proposal, which scenario of such a cluster should be taken as representative, because the centroid (as proposed by Brauers and Weber (1988)) does not comply with the nominal scale of the impact variables. Both, top down and bottom up procedures, are time and labour consuming, especially when S^* is large.

In order to simplify the presentation of the proposed procedures of scenario selection two additional scenario properties have to be defined. The *distance d* between two scenarios S_k and S_ℓ is simply the number of impact variables, which are different

$$d(S_k, S_\ell) = \sum_{i=1}^{n} \begin{cases} 1 & \text{if } y_i(S_k) \neq y_i(S_\ell), \\ 0 & \text{otherwise.} \end{cases} \tag{7}$$

Because it is assumed that impact factors are variables on a nominal scale (the levels are not ordered, see above), the size of a difference between two levels of an impact factor is not taken into consideration (even if—in a specific application—such a difference could be defined).

A scenario S_ℓ is a *neighbour* of scenario S_k if and only if the two scenarios differ only in one impact variable, i.e. $d(S_k, S_\ell) = 1$.

The objective of the scenario selection procedures is to obtain a final set S^{final} of scenarios with a small number of consistent and significantly different scenarios. The consistency of a scenario is measured by the consistency indicators given in Eqs. (3)–(6). The difference between two scenarios is measured as the number of different levels (Eq. (7)). After the application of the proposed procedures the resulting sets of scenarios are compared with each other in order to assess the reliability of the three selections. The efficiency is investigated by a comparison of the consistency of the resulting scenarios with all their neighbours.

2.3. Prerequisites

The proposed procedures for scenario selection cannot always be applied. At first they are restricted to formative scenario analyses characterized above. In this case it means that an encompassing list of impact variables exists, which is sufficient to conceptualise the investigated system. It also means that the defined levels of the impact variables characterize all the possible levels an impact factor can take. The next requirement is, that the consistency matrix can be assessed, i.e. the possible scale of the consistency ratings (see Table 1) applies to all combinations of impact factor levels and there are experts, which are able to do these ratings. In general, encompassing detailed investigations are required for that to supply the necessary information. It is also assumed, that all consistency ratings can be done with the same certainty, because the consistency indicators do not account for possible differences.

A fundamental assumption is, that the consistency is a binary relation between pairs of impact factor levels (Scholz and Tietje, 2002; Götze, 1993; Brauers and Weber, 1988). Interactions between more than two impact variables are neglected. This is significant, if a third variable modifies the consistency rating of two other variables. If this is recognized during the assessment of the consistency matrix, then a redefinition of impact variables or their levels may be necessary. A violation of any of the prerequisites may also forbid an application of a formative scenario analysis and require the change to another type of scenario analysis.

The proposed procedures for scenario selection all make use of the estimated consistencies as described above and thus do not take any probabilities of the different levels of impact variables into account.

3. Three procedures for scenario identification

To finally obtain a set S^{final} of scenarios three different procedures are proposed, which are explained below and which have the following rationales:

- Procedure *Local Efficiency*: Calculate the local efficiency of all scenarios in S^* and select the scenarios with a maximum local efficiency.
- Procedure *Distance-To-Selected*: First select the scenario with the largest multiplicative consistency and then iteratively calculate the "distance-to-selected" and select one of the most consistent and most distant scenarios.
- Procedure *Max-Min-Selection*: Specify the required minimum distance between the final scenarios and then subsequently select the most consistent scenario that exceeds the distance criterion for all previously selected scenarios.

3.1. The local efficiency procedure applying combinatorial optimisation

For this procedure the consistency of a scenario S_k is calculated together with the consistencies of all its neighbours S_{kB}. The scenario S_k is locally efficient, if the consistency of S_k is greater than (or equal to) the consistency of each of its neighbours S_{kB}. The idea of this procedure for scenario selection is, that only locally efficient scenarios are taken into consideration.

The number B_n of neighbours is constant and hence the same for each scenario. It depends on the number of impact variables n and the number of the possible levels n_i of each impact variable i

$$B_n = \sum_{i=1}^{n} (n_i - 1).$$

If, for example, only two levels are allowed for each impact factor, the number of neighbours equals the number of impact factors.

The *local efficiency* of a scenario S_k is now defined as the number of neighbours with a lower consistency. The comparison of the consistency of two scenarios can be done using each of the consistency indicators defined above ($c^*_{\text{add}}(S_k)$ (Eq. (3)), $c^*_{\text{mult}}(S_k)$ (Eq. (4)), $c^*_{\text{inco}}(S_k)$ (Eq. (5)), $c^*_{\text{conL}}(S_k)$ (Eq. (6))) and using a strong indicator ('less than') or a weak indicator ('less than or equal to'):

$$I^s_j(S_i, S_k) = \begin{cases} 1 & \text{if } c^*_j(S_i) < c^*_j(S_k), \\ 0 & \text{otherwise}, \end{cases} \tag{8}$$

$$I^w_j(S_i, S_k) = \begin{cases} 1 & \text{if } c^*_j(S_i) \leqslant c^*_j(S_k), \\ 0 & \text{otherwise}, \end{cases} \tag{9}$$

where $j \in \{\text{add}, \text{mult}, \text{inco}, \text{conL}\}$. The calculation is according to

$$LE^x_j(S_k) = \sum_{S_i \in S_{kB}} I^x_j(S_i, S_k), \tag{10}$$

where $LE^x_j(S_k)$ is the jth type of local efficiency, either strong ($x = \text{s}$) or weak ($x = \text{w}$), of scenario S_k, the summation goes over all neighbours $S_i \in S_{kB}$ of S_k and I^x_j is the efficiency indicator (Eqs. (8,9)).

The *local efficiency procedure* results in few scenarios to be selected as final scenarios. Depending on the specified consistency matrix, the following difficulties can occur:

- When a weak efficiency indicator is applied, it is possible to find several similar scenarios (which are neighbours or have a small distance between them) with all being locally efficient. Although these scenarios are a local maximum, they exhibit a *broad maximum*. In such a case the set of these similar scenarios can be conceived of as only one scenario with some impact factors being uncertain. Because broad maxima are often obtained when the number of inconsistencies $\left(LE^{\text{w}}_{\text{inco}}\right)$ or the consistency level $\left(LE^{w}_{\text{conL}}\right)$ are used, the application of the additive $\left(LE^{w}_{\text{add}}\right)$ or multiplicative $\left(LE^{w}_{\text{mult}}\right)$ local efficiencies is preferred.
- When a strong efficiency indicator is applied, it may occur that too few scenarios are locally efficient. For example, if there exist only two different levels per impact factor then only two scenarios might be locally efficient. In this case the number of levels of some impact factors may be increased (if possible). But other efficiency indicators or other procedures for scenario selection could probably also help analysing the structure of the set S^* of filtered scenarios.
- It may occur, that there is a sequence of scenarios with the same consistency, which are all neighbours (such as S_1 is a neighbour of S_2, S_2 is a neighbour of S_3 and so on until the last scenario, which might again be a neighbour of S_1).

A strong type of local efficiency would not identify these scenarios as locally efficient.

The *local efficiency procedure* overcomes a drawback of cluster analysis to identify characteristic groups among the set of filtered scenarios (as proposed by Scholz and Tietje (2002) and Götze (1993)). Although such a cluster analysis is straightforward, it does not identify a typical representative of each cluster (see above). The *local efficiency procedure* does not determine the clusters, but provides the desired representatives as the proposed selection of scenarios.

3.2. The distance-to-selected procedure applying harmonic averages

This procedure for scenario selection does not automatically yield a set of scenarios. Instead, it consists of simple rules for the scenario analyst how to proceed and an indicator, which provides necessary information for this procedure. The steps of this procedure are as follows.

Step 1. Select an initial scenario S_i. A reasonable choice would be to select the most consistent scenario as calculated with the multiplicative or additive consistency indicator. But, if there are reasons to include a specific scenario in the final set of scenarios, an individual choice could be made. Of course, it is recommended to check the consistency of this scenario.

Step 2. For all the filtered scenarios (see above) calculate the distance to the selected scenario(s). If there is only one scenario, this can be easily done using Eq. (7). If there are already more scenarios selected, calculate the harmonic mean of the distances between a given scenario and the selected scenarios. If S_{f} is one of the filtered scenarios and S_{selected} is the set of already selected scenarios (initially consisting of the initial scenario S_i) then the *distance-to-selected* (dts) is defined as the harmonic mean of the distance between the current scenario S_{f} and the selected scenarios, namely

$$\mathrm{dts} := \left(\sum_{S_j \in S_{\mathrm{selected}}} \frac{1}{d(S_j, S_{\mathrm{f}})} \right)^{-1}. \tag{11}$$

The distance $d(S_j, S_{\mathrm{f}})$ is nonzero because dts is only interesting for those filtered scenarios, which are not already selected. The purpose of dts is to assure that—when searching for an additional scenario—those scenarios are of particular interest, which are consistent but not similar to one of the already selected scenarios. An arithmetic or absolute mean cannot be used for the calculation of dts, because small distances would compensate for large distances. A quadratic mean (such as the sum of squares) would emphasise a large distance and hence an existing small distance to one of the selected scenarios would be ignored. Hence a harmonic mean distance is appropriate, because it is low if at least one of the distances $d(S_j, S_{\mathrm{f}})$ is low. Instead of the minimum distance between S_{f} and any of the selected scenarios (which measures the distance of S_{f} to a single scenario), a large dts indicates a large distance to all of the selected scenarios (which is the desired characteristic).

Step 3. Select the next scenario as one with a large consistency and a large *distance-to-selected* (dts). The trade-off between the consistency and the dts depends on the intuition of the scenario analyst. On the one hand this is a disadvantage, because there is a subjective influence, but on the other hand this is a big advantage, because this step can be done together with experts who already specified the consistency matrix and hence the process of scenario selection is transparent to them. After having selected an additional scenario return to step 2, if not yet satisfied with the selected scenarios and if the obtained dts values are not too small.

3.3. The max-min-selection using a simple algorithm

In this procedure a consistency indicator has to be defined, which determines the selections. In general the multiplicative consistency indicator given by Eq. (4) is recommended because it is not compensating. The attempt to improve the additive indicator (Eq. (3)), for example (see Scholz and Tietje, 2002) by defining the consistency value of '*inconsistent*' as −99 (instead of −2 as in Table 1), introduces a lack of rigorousness into the scenario analysis. The steps of the max-min-selection are as follows:

1. Define the minimum distance $d_{\min}$ between all scenarios to be selected as being equal to the number of impact factors.
2. Select the most consistent scenario as the initial scenario S_i.
3. Among those scenarios of S^*, which are not yet selected or tested, identify the scenario S_{test} with the maximum consistency. If there is no scenario left, show the set of selected scenarios and continue with step (7).
4. If the distance between S_{test} and each of the selected scenarios is greater than or equal to $d_{\min}$ then proceed to the next step (5), otherwise repeat the previous step (3).
5. Add S_{test} to the list of selected scenarios.
6. If there are still scenarios in S^*, which are not yet tested or selected, go to step (3), otherwise show the set of selected scenarios.
7. If there are too few scenarios (which might occur due to the consistency matrix and the filtering procedure), reduce the minimum distance $d_{\min}$ between all scenarios to be selected by 1 and repeat again from step 2.

For each minimum distance from n (equal to the number of impact factors) down to 1 this procedure will provide a set of scenarios, which fulfil the filter criteria, which have all a minimum distance of $d_{\min}$ from each other, and which are most consistent among all other possible selections fulfilling the first two criteria. The analysis of the number of the scenarios with given minimum distance gives very helpful information about the set of filtered scenarios. It is recommended to use the set of scenarios with the required number of scenarios. The examples below will show, that this algorithm is very efficient in finding a small set of consistent scenarios, in which the distances between the scenarios are all large.

4. Application and results

4.1. Synthesis group "economy" of ETH-UNS Case Study 1998

In order to test the proposed approaches they have been applied for several consistency analyses, most of them have been conducted within the ETH-UNS Case Studies. In the 1998 case study 'Opportunities in the Klettgau Region' (Scholz et al., 1999) a formative scenario analysis (Scholz and Tietje, 2002) was conducted to assess the possibilities for a sustainable regional development under an economic and environmental perspective. During this analysis, 14 impact factors with three or four levels have been identified to represent the future development of the region (see Table 2). They have been described in detail and assessed with respect to the mutual consistency of their levels. The consistency ratings were −2: '*inconsistent*' (occurring 45 times), −1: '*hindering*' (188 times), 0: '*unrelated*' (270), 1: '*supporting*' (341), and 2: '*inducing*' (95) (the resulting consistency matrix is not presented here, but can be obtained from the author). The result was a very large number of about 11 million combinatorial scenarios. During the ETH-UNS Case Study 1998, the study team conducted a consistency analysis applying a bottom-up procedure (looking for similarities among the 200 most consistent scenarios), an additional cluster analysis (within the 200 and 10000 most consistent scenarios), and a top-down procedure. The first two procedures could identify two scenarios, *"Small Changes"* (see Table 2) and *"Ecologic, cooperative and region-oriented"* (see below). The third (top-down) procedure during the ETH-UNS Case Study could not identify scenarios, but arrived at a kind of 'sub-scenarios' which identified possible developments of the Klettgau (for detailed results see Scholz et al., 1999).

4.2. Application of the proposed procedures

To prepare the scenarios for the proposed approaches the following filtering was applied. The first try was to exclude scenarios with at least one inconsistency, but the remaining number of 50,000 scenarios was considered too large. To sharpen this filter, the second try was to take only those scenarios which have a minimum consistency level of zero. For these scenarios the consistency rating of any pair of impact factors was 0, 1, or 2. This resulted in eight scenarios, which were very similar and hence this filter was considered too sharp. The

Table 2
The four scenarios and their characteristics obtained from 467 filtered scenarios with max-min-selection

Impact factor (number of levels)	Scenario number 5692032 *"Small changes"*	Scenario number 11010914 *"Ecology"*	Scenario number 210042 *"Limited"*	Scenario number 5080579 *"Globalisation"*
Geographical range of trade (4)	Current state	Agglomeration	***Agglomeration***	Global[a]
Agricultural production (3)	Current state	Ecological orientation	More intense[a] production	***More intense production***
Competitiveness (3)	Current state	Innovation	Current state[a]	Assimilation[a]
Company structure (3)	Current state	Natural resources	***Current state***	Small business[a]
Kind and amount of goods (3)	Current state	Diversification	Concentration[a]	Concentration[a]
Swiss German border (3)	Current state	Reduction	Consolidation[a]	Reduction[a]
Politics (3)	Current state	Opening	Closing[a]	Opening[a]
Economic conditions (3)	Current state	Improvement	Decline[a]	***Current state***
Mentality (3)	Current state	Opening	***Inward orientation***	***Current state***
Credit criteria (3)	Current state	Sustainable	***Current state***	Short-term[a]
Infrastructure (3)	No change	Distributed enlargement	No change[a]	Distributed enlargement[a]
Consumer behaviour (3)	Current state	Qualitative	Quantitative[a]	***Quantitative***
Local job market (3)	Current state	Increasing supply	Low supply[a]	***Current state***
Local politics (3)	Current state	Cooperation	Short-term orientation[a]	Current state[a]
Multiplicative consistency (Eq. (4))	1.01×10^{26}	7.55×10^{25}	1.64×10^{17}	3.08×10^{16}
Additive consistency (Eq. (3))	98	98	63	61
Number of inconsistencies (Eq. (5))	0	0	0	0
Consistency level (Eq. (6))	0	−1	−1	−1
LE^s_{mult}	31	31	30	30
LE^s_{add}	31	30	29	28
LE^s_{inco}	4	15	17	15
LE^s_{conL}	28	15	17	15
LE^w_{mult}	31	31	30	30
LE^w_{add}	31	31	31	29
LE^w_{inco}	31	31	31	31
LE^w_{conL}	31	31	31	31

[a] These levels coincide when the *local efficiency* and the dts procedures are applied (the first two scenarios coincide as a whole). The levels in bold font are different for at least one of the other procedures.

third try was the requirement, that one of the local efficiencies LE^w_{mult} or LE^w_{add} should be at least 29 (the maximum value was the number of 31 neighbours). The resulting 467 scenarios proved to be consistent and different enough.

When applying the *Local Efficiency* Procedure the calculation of the local efficiencies shows, that there are 11 scenarios which are either additively or multiplicatively locally efficient. Unfortunately there are several scenarios, which are similar. Starting with the highest similarity (neighbour scenarios), from each scenario pair the one with the lower consistency is cancelled. This results in four scenarios with a minimum distance of 8.

In the *Distance-to-Selected Procedure* the scenario with the highest multiplicative consistency was taken first. Then, for each of the remaining scenarios, the distance to this scenario was calculated with Eq. (7). From those scenarios with distance 14 the most consistent scenario was selected second. Then, again for each of the remaining scenarios, the distance to this selection was calculated with Eq. (11). The third scenario was added to the selection, because it had a dts of 6.24 with the highest multiplicative consistency. After the next recalculation of dts (Eq. (11)) for all remaining scenarios the fourth scenario was selected with a dts of 3.33. After the following computation the maximum dts has lowered to 2.5 and the procedure was stopped because the resulting scenario had seven impact factors with the same levels as the third scenario.

The application of the *max-min-selection* resulted in the four scenarios shown in Table 2 for a minimum distance of 10. The algorithm firstly finds two scenarios with a minimum distance of 14 so that all impact factors have different levels. If the minimum distance between the scenarios is lowered to 12, a third scenario is obtained. This scenario is very similar to one of the four scenarios obtained with a minimum distance of 10 (only the two impact factors 4 and 10 have different levels).

4.3. Results

The results of the scenario selection procedures are different sets of scenarios. Table 2 shows the set produced by *max-min-selection*. These scenarios were—for convenience and in accordance to the original case study—labelled *"Small Changes", "Ecology", "Limited"*, and *"Globalisation"*.

The first scenario is the same as the scenario *"Small Changes"* identified in the ETH-UNS case study (see above). The second scenario *"Ecology"* has only one other level than the scenario *"Ecologic, cooperative and region-oriented"* from the original study, namely for the geographical range of trade. The reason for the difference is, that the proposed algorithm does not take into account the grouping of scenarios by the cluster analysis conducted in the original study, where a cluster of ecological, cooperative and region-oriented scenarios was identified. The more local trading within the Klettgau *"Region"* (as in the scenario from the original study) implies a smaller multiplicative consistency than the trading orientation towards the *"Agglomerations"* (Schaffhausen and Zürich) in the scenario *"Ecology"*. The additive consistency of both scenarios is the same (note the different scales in Table 1).

Fig. 1 presents all scenarios obtained with all three proposed procedures. The similarity of each pair of scenarios is indicated by the lines connecting these scenarios. The thicker the connecting line, the larger is the number of equal levels. All proposed procedures selected the same first two scenarios (*"Small Changes"*, *"Ecology"*). The last two scenarios resulting from the three approaches were different. But, although determined by very different methods, they have a large number of equal levels so that they are referred to under the same labels *"Limited"* and *"Globalisation"*. Table 2 displays, which levels of the two scenarios coincide when any of the proposed procedures is applied. It can be seen, that scenarios with lower consistencies have some uncertain variables depending on the proposed scenario selection procedures. This demonstrates the degree of convergent validity, by which the scenario selection can be conducted. Nine other consistency analyses

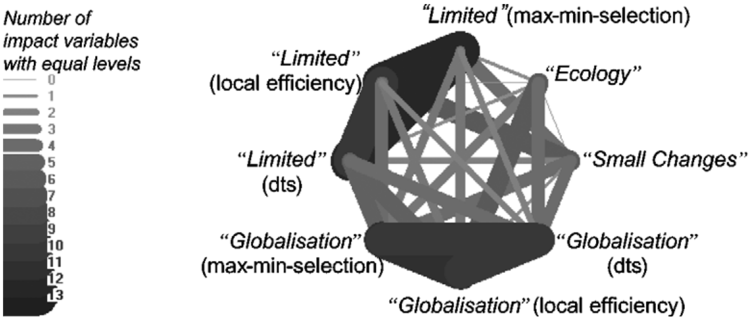

Fig. 1. Number of impact factors with equal levels for the scenarios determined with the proposed procedures local efficiency, distance-to-selected (dts), and max-min-selection.

conducted during ETH-UNS case studies between 1994 and 2002 show principally similar results (data not shown).

The consistency of the selected scenarios is shown in Fig. 2. The multiplicative and additive consistency indicators show the same patterns for the different sets of scenarios. Differences between the selection methods can be found for scenarios with lower consistency. The selection by local efficiency tends to select the most consistent scenarios. For the scenario "Globalisation" the consistency difference due to the selection procedure is the largest, the additive consistency ranges from 54 (*distance-to-selected*) to 69 (*local efficiency*). Thus even the largest consistency difference between scenarios selected with different procedures was found to be small, about six times smaller than the scenario with the largest consistency and about three times smaller than the range between the highest (additive consistency 98 of the scenario "Small Changes") and lowest consistency (additive consistency 54 of the scenario "Globalisation").

The difference between pairs of scenarios (as shown in Fig. 1) does not answer the question, which set of scenarios selected by one of the proposed methods shows the most different scenarios. Therefore, for each scenario the distance to the other three scenarios (selected with the same selection method) has been calculated using Eq. (11). The results are shown in Fig. 3. It can be seen, that *max-min-selection* and *distance-to-selected* perform better than the *local efficiency selection*.

Each scenario selection procedure was used to identify four scenarios. The *local efficiency selection* first produced six multiplicatively (five strong), and seven additively (one strong) locally efficient scenarios. The two scenarios *"Small Changes"* and *"Ecology"* are both, multiplicatively and additively (weak) locally efficient. The scenario *"Limited"* is additively but not multiplicatively, and the scenario *"Globalisation"* multiplicatively but not additively locally efficient (Fig. 4). Hence, the selection depends on the type of local efficiency used. Another disadvantage is, that local efficiency does not imply a large distance among the scenarios. Because the full range of distances occurs (from scenario neighbours up to the maximum distance) the question remains, which is the minimum distance that should be required for the final set of scenarios. For the multiplicative efficiency an additional (fifth) scenario would be selected, if nine same levels (with the "Globalisation" scenario) would be acceptable. For the additive efficiency an

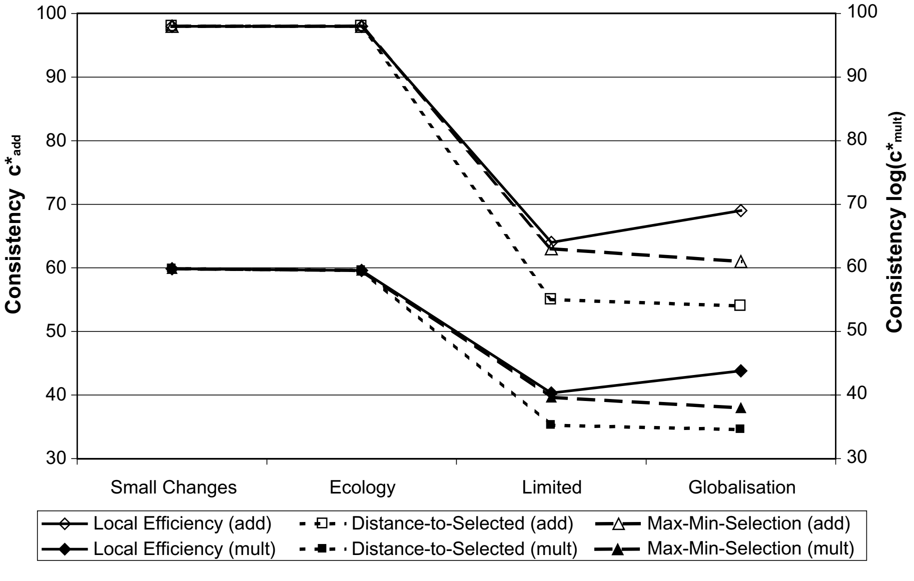

Fig. 2. Additive c^*_{add} and multiplicative c^*_{mult} consistency of scenarios selected with different procedures.

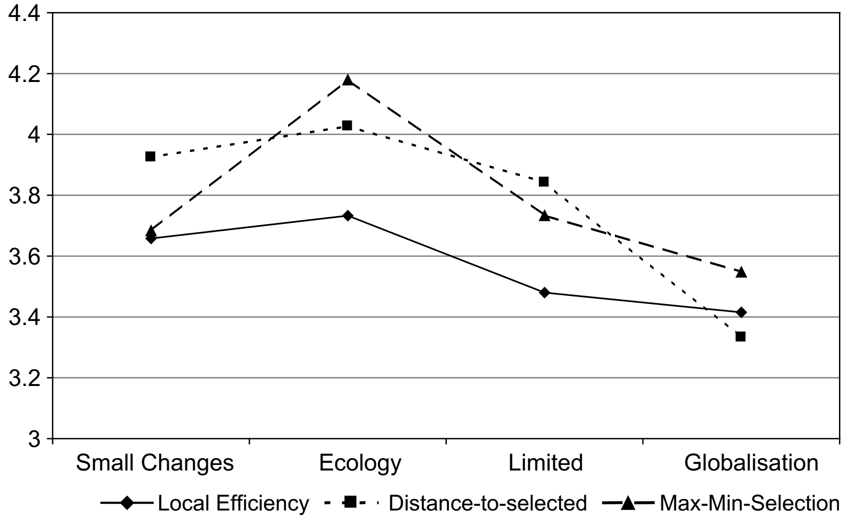

Fig. 3. Distance (according to Eq. (11)) of each scenario to all other scenarios selected with the same selection method.

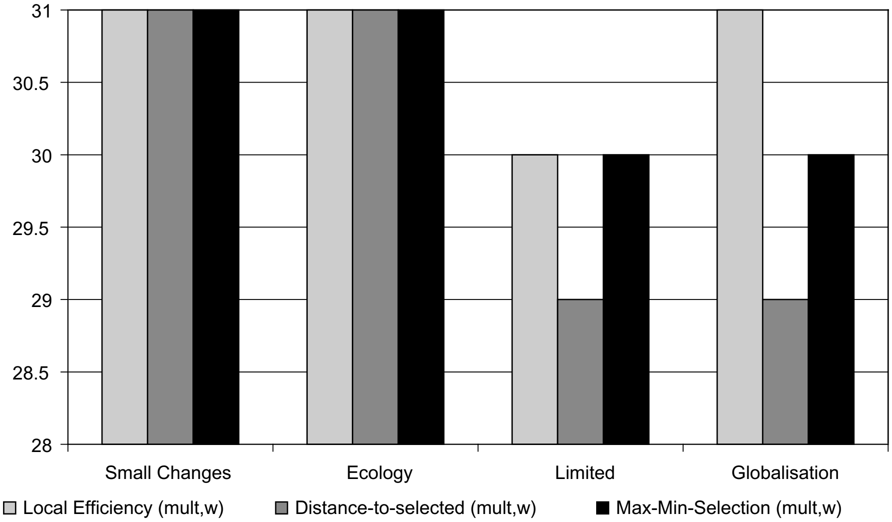

Fig. 4. Weak multiplicative local efficiency of the scenarios obtained by the three selection procedures.

additional (fifth) scenario would be selected, if eight same levels (between two pairs of scenarios) would be acceptable. Although the number of selected scenarios is small, the exact number depends on the required minimum distance between them. This also holds applying the other selection procedures. The distance-to-selected procedure iterates until there is no scenario left with a distance above the required minimum distance between scenarios. The *max-min-selection* even uses the required minimum distance between scenarios as a parameter.

Given the required minimum distance each scenario selection procedure should be reliable and produce a uniquely determined set of scenarios. Depending on the type of local efficiency (multiplicatively, additively, or both) different final sets of scenarios are obtained. If only the weak multiplicative local efficiency is used, the scenario *"Limited"* is not selected instead of an additional scenario, which could be labelled *"Ecological Globalisation"*, because it has eight impact factors with the same levels as "Ecology" and seven impact factors with the same levels as "Globalisation". If only the additive local efficiency is used, nearly the same scenario *"Ecological Globalisation"* (two different impact factor levels) is selected and the scenario *"Globalisation"* is not selected. Additionally a scenario is selected, which partly equals "Small Changes" and partly "Ecology". Considering a required minimum distance, which exceeds half the number of impact factors, both variants (selection with only the multiplicative or only the additive local efficiency) select three of the four scenarios which resulted from the use of both kinds of local efficiency. Because the local efficiency of a scenario is fixed, the recommended use of both local efficiency indicators (as described above) can be considered reliable.

The above described distance-to-selected procedure leads to a unique selection. This is because among the scenarios with the largest dts (distance-to-selected) the most consistent scenario is selected. Because there would be slightly more consistent scenarios with a slightly less dts, other scenarios could be selected. But the applied variant of the dts procedure is straightforward and rigorous and thus recommended. Experience from several scenario analyses (data not shown) reveals that the selected scenarios show an almost as high consistency as if selected with local efficiency or max-min-selection (see Fig. 2).

Given the minimum distance as the required parameter the max-min-selection leads to exactly the same scenarios, regardless whether the multiplicative or additive consistency indicator is used. Occasionally, this might not be the case, because scenarios exist with the same additive and/or multiplicative consistency.

Efficiency as a criterion of the selected scenarios tries to evaluate, whether the scenario is a good (in the sense of the most consistent) representative of a group of scenarios. Of course, the *local efficiency selection* performs best with respect to this criterion (see Fig. 4). But it is not unlikely that chains of neighbour scenarios occur, in which the consistency increases (strongly) monotonously. Such chains are observed starting from the scenarios *"Limited"* and *"Globalisation"* and ending at the scenario with the highest consistency (namely "Small Changes").

5. Discussion and conclusions

The proposed procedures for scenario selection were applied to a scenario analysis with a large number of impact variables and levels (Scholz et al., 1999). This application illustrates, that they fit well into the framework of formative scenario analysis methods (Götze, 1993; Scholz and Tietje, 2002), they can be easily used, and have several advantages over the as yet available cluster analysis. Cluster analysis does not regard the consistency of the scenarios, gives not a good representative of the cluster (Brauers and Weber, 1988), requires considerable effort (Wiek et al., 2001) and hence becomes less practicable for large-scale scenario analyses.

Many authors specified criteria for the validity of the single scenarios (see e.g., Götze, 1993; von Reibnitz, 1992). These criteria include for instance intelligibility, comprehensibility, credibility, plausibility, completeness of scenarios and many other. This investigation claims no direct improvement of such kind of scenario quality, because this would be related to the quality of the definition and derivation of impact factors, their levels, and their mutual consistency and hence is related to the purpose of the scenario analysis, the involved disciplines and involved people. On the contrary, this investigation assumed that the above specified criteria are fulfilled and tries to improve the subsequent step of scenario selection.

As in the presented results the experience with several scenario analyses within ETH-UNS case studies shows, that the indicators (Eqs. (3)–(6)) and the proposed procedures largely support the investigation and evaluation of a consistency matrix. The resulting final sets of scenarios include a small number of consistent and different scenarios. The results showed, that the selection procedures are reliable. The comparison of the scenarios revealed, that the selection procedures have a high convergent validity (i.e. different methods lead to similar results, Scholz and Tietje, 2002, p. 336): Those scenarios, which have a consistency considerably lower than the highest value, are not uniquely determined by the three procedures, but the differences are small. Note that this is the first investigation assessing the (convergent) validity of the scenario selection.

The *local efficiency scenario selection* relies on the idea of a local consistency optimum. The idea is attractive, but the results depend on whether a strong or weak, multiplicative or additive efficiency is used. Although a careful application leads to a reliable scenario selection, the proposed procedure cannot be applied without additional consideration of the kind of optimum (broad maximum, chains of scenario neighbours). The main disadvantage seems to be that the distance between the resulting scenarios is not regarded. The strong efficiency tends to select too few, the weak efficiency too much scenarios. The local efficiency of a scenario does not perfectly indicate whether a scenario is a good representative of a set of similar scenarios (such as a cluster), but can be effectively used to find possible representatives. Therefore the local efficiency can also support the application of cluster analysis for scenario selection.

Although developed independently, the local efficiency formally defined here can be conceived of as quantifying a similar qualitative goal of scenario selection given by von Reibnitz. She defined scenarios as *internally stable*, if they—stressed by disturbances—do not change to more consistent scenarios (von Reibnitz, 1992, p. 52). This might be interpreted as: An internally stable scenario is more consistent than all its neighbours and hence locally efficient. Von Reibnitz argued that an internally stable scenario is valid for a longer period than an unstable scenario, because—under stress—the latter would change to a more consistent scenario.

The *distance-to-selected approach* seems to be the most transparent approach. Each step can be traced and reasonably justified. Both criteria, consistency of and difference between scenarios are regarded. The scenario analyst has direct influence on the selected scenarios. This can be an advantage, because the participating experts can be directly involved, but also a disadvantage, because the selection becomes more subjective (Rosenhead and Mingers, 2001, p. 6). But the influence of the scenario analyst is very limited, even though he might select a slightly different scenario and thus the dts of the remaining scenarios changes. The differences between final sets of scenarios selected with dts by different scenario analysts are smaller than the differences presented in Fig. 1 between final sets of scenarios selected with the three proposed procedures.

The *max-min-selection* is simple and clear and also regards both, consistency and difference between the scenarios. The algorithm is as quick, that it first is hard to trust in the results. This makes the approach susceptible to become a standard of scenario selection. The use of a multiplicative or an additive consistency indicator leads to almost the same scenarios. A drawback of this approach is that different scenarios may be obtained, when different minimum distances are required: In our case, when the minimum distance is 12, three scenarios are selected, whereas a minimum distance of 10 results in four scenarios. In both cases the first two scenarios are the same. In this case the third scenario of the former case ($d_{\min} = 12$) is similar (two different levels) to one of the last two scenarios in the latter case ($d_{\min} = 10$). Although similar results were obtained in the nine other applications within the ETH-UNS case studies, it remains unproven.

The applications and the results show, that the proposed approaches—*local efficiency*, *distance-to-selected*, and *max-min-selection*—largely solve the problem of identifying a small reliable and efficient set of consistent scenarios. The small differences between the results of the different approaches do not only show their convergent validity but also reveal, which scenarios are not completely determined by the underlying consistency matrix and hence have impact factors with uncertain levels.

One of the most important aspects of scenario analysis (although beyond the primary focus of this manuscript) is, that the selected scenarios and the differences among them have to be translated into visual graphical representations and into narratives, which can be communicated to the decision makers. Several such visualizations have been implemented into the scenario selection software (Tietje, 2003).

The proposed approaches select sets of scenarios with high quality with respect to the criteria consistency, difference, small number, reliability, and efficiency. The scenario selection becomes easier and more comprehensible. In this sense the application of the proposed approaches supports decisions to be made on the basis of the scenarios. Nevertheless, the selected scenarios still depend on the plausibility and reliability of the consistency matrix and on the overall quality of the scenario analysis as a whole. The convergent validity shows, that the scenario analyst—by choosing a selection method—introduces only a small bias into the scenario selection.

Acknowledgements

I acknowledge the support by the ETH Zürich, Chair of Environmental Sciences: Natural and Social Sciences Interface (ETH-UNS, Prof. R.W. Scholz). Several scenario analyses were conducted during ETH-UNS Case Studies and the proposed approaches could be tested on these data. I am also grateful to Claudia Binder, Arnim Wiek, and Susanne Ulbrich, who applied and/or commented on the proposed approaches and earlier versions of the manuscript.

References

Bossel, H., 1998. Earth at a crossroads paths to a sustainable future. Cambridge University Press, Cambridge.

Brauers, J., Weber, M., 1988. A new method of scenario analysis for strategic planning. Journal of Forecasting 7, 31–47.

Collins, H., 1995. Collins English Dictionary. Harper Collins Publisher & Novell Inc.

Cooke, R.M., 1991. Experts in Uncertainty. Oxford University Press, New York, NY.

ETH-UNS. (2003, 13.2.2003). Welcome to the ETH-UNS Case Study [Website]. Sandro Bösch, ETH Zürich, Department of Environmentral Sciences: Natural and Social Science Interface, Switzerland. Retrieved 11.8.2003. Availabe from <http://www.fallstudie.ethz.ch/fs/fs_allg_e.html>.

Godet, M., 1986. Introduction to la prospective. Seven key ideas and one scenario method. Futures 18 (2), 134–157.

Götze, U., 1993. Szenario-Technik in der strategischen Unternehmungsplanung (Scenario technique for strategic business planning), second ed. Deutscher Universitäts-Verlag, Wiesbaden.

Graf, H.G., 2002. Economic Forecasting for Management: Possibilities and Limitations. Quorum Books, Westport, Conn.

Hassler, S., Schärli, M.A., 1996. Reliabilität und Validität der Szenarioanalyse Grosses Moos (Reliability and validity of the scenario analysis "Grosses Moos"). Diploma Thesis. Zürich: ETH-UNS.

Heugens, P.P.M.A.R., van Oosterhout, J., 2001. To boldly go where no man has gone before: Integrating cognitive and physical features in scenario studies. Futures 33 (10), 861–872.

Kahn, H., Wiener, A.J., 1967. The Year 2000. Macmillan, London.

MacNulty, C.A.R., 1977. Scenario development for corporate planning. Futures 9, 128–138.

Meadows, D.L., Behrens, W.W., Meadows, D.H., Nail, R.F., Randers, J., Zahn, E.K.O., 1974. The Dynamics of Growth in a Finite World. Productivity Press, Cambridge, MA.

Missler-Behr, M., 1993. Methoden der Szenarioanalyse (Methods of scenario analysis). Deutscher Universitäts-Verlag, Wiesbaden.

Rosenhead, J., Mingers, J. (Eds.), 2001. Rational Analysis for a Problematic World Revisited. Problem Structuring Methods for Complexity, Uncertainty and Conflict. Wiley, Chichester.

Ruth, M., Hannon, B., 1997. Modeling Dynamic Economic Systems. Springer, New York.

Scholz, R.W., Tietje, O., 2002. Embedded Case Study Methods: Integrating Quantitative and Qualitative Knowledge. Sage, Thousand Oaks. pp. xvi+392.

Scholz, R.W., Koller, T., Mieg, H.A., Schmidlin, C., 1995. Perspektive "Grosses Moos"—Wege zu einer nachhaltigen Landwirtschaft. ETH-UNS-Fallstudie 1994 (Paths towards sustainable agriculture in the region 'Grosses Moos'. ETH-UNS Case Study 1994), vdf, Zürich.

Scholz, R.W., Bösch, S., Carlucci, L., Oswald, J. (Eds.), 1999. Nachhaltige Regionalentwicklung: Chancen der Region Klettgau (Sustainable Regional Development: Opportunities of the Klettgau Region). Rüegger, Zürich.

Tietje, O., 2003. Systaim: KD—Consistency Analysis, Version 2.0. Zürich: o.tietje.systaim. Available from <http://www.systaim.ch>.

von Reibnitz, U., 1992. Szenario-Technik (Scenario Techniques), second ed. Gabler (English version by McGraw-Hill, 1989, out of print), Wiesbaden.

Wiek, A., Supported by Scholz, R.W., Deér, S., Liechtenhan, W., Tietje, O., Gerecht, B., 2001. Formative Szenarioanalyse zur Erstellung von Rahmenszenarien für die Entwicklung der Landschaftsnutzung im Kanton Appenzell Ausserrhoden (Formative Scenario Analysis for Global Scenarios of the Canton Appenzell Ausserrhoden), ETH-UNS, Zürich.