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METHODS

Evaluating strategies for sustainable development: fuzzy logic reasoning and sensitivity analysis☆

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Abstract

Sustainable decision-making involves political decisions at the local, regional, or national levels, which aim at a balanced development of socio–environmental systems. A fundamental question in sustainable decision-making is that of defining and measuring sustainable development. Many methods have been proposed to assess sustainability. Recently, a model has been developed, called Sustainability Assessment by Fuzzy Evaluation (SAFE), which uses fuzzy logic reasoning and basic indicators of environmental integrity, economic efficiency, and social welfare, and derives measures of human (HUMS), ecological (ECOS), and overall sustainability (OSUS). In this article, we perform sensitivity analysis of the SAFE model to identify the most important factors contributing to sustainable development. About 80 different indicators are tested and classified as promoting, impeding, or having no effect on the progress toward sustainable development. The proposed method is applied to the Greek and American economies. The conclusion is that there is no unique sustainable path and, accordingly, policy makers should choose different criteria and strategies to make efficient sustainable decisions for each country.

Keywords: Sustainable development; Decision-making; Indicators of sustainability; Fuzzy logic

1. Introduction

Sustainable development is nowadays the goal, in words at least, of most politicians and decision makers. Since the publication of the Brundtland report in 1987 [World Commission on Environment and Development (WCED), 1987], the concept of sustainability has gained increasing attention among policy makers and scientists which culminated during the 1992 Earth Summit held in Rio de Janeiro. Among the results of the Earth Summit, Agenda 21 is a comprehensive list of actions needed to achieve sustainable development [United Nations Conference on Environment and Development (UNCED), 1992]. Leaders from over 150 states committed themselves to undertaking actions which will render future development sustainable but without the scientific tools to guide policy making towards a sustainable path (HMSO, 1994). Decisions leading to sustainable development ought to be based on good science and adequate information. Thus, data are needed about environmen-

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tal, social, and economical factors known as indicators of sustainability. Sustainable projects and optimal strategies for development necessitate answering four fundamental questions: "why unsustainable development occurs", "what is sustainability?", "how can it be measured?", and "which factors affect it?" (Atkinson et al., 1999).

There is evidence that development is currently unsustainable. Ozone depletion, global warming, depletion of aquifers, species extinction, collapse of fisheries, soil erosion, and air pollution are among the obvious signs of ecological distress (Brown et al., 2000). Our society is also showing similar signs due to poverty, illiteracy, AIDS, social and political unrest, and violence (International Union for the Conservation of Nature/United Nations Environment Program/WorldWide Fund for Nature (IUCN/UNEP/WWF), 1991; United Nations Environment Programme (UNEP), 1992).

Recently, fuzzy logic has been proposed as a systematic tool for the assessment of sustainability. Fuzzy logic is capable of representing uncertain data, emulating skilled humans, and handling vague situations where traditional mathematics is ineffective. Based on this approach, we have developed a model called Sustainability Assessment by Fuzzy Evaluation (SAFE), which uses basic indicators of environmental integrity, economic efficiency, and social welfare as inputs, and employs fuzzy logic reasoning to provide sustainability measures on the local, regional, or national levels (Phillis and Andriantiatsaholiniaina, 2001).

This paper provides an approach to sustainable decision-making on the national level using sensitivity analysis of the SAFE model. Sensitivity analysis reveals the most important factors contributing to a sustainable society. The proposed method is applied to a number of selected economies. It becomes clear that there is no unique sustainable path and, accordingly, policy makers should choose different criteria and strategies to make efficient sustainable decisions for each country.

It should be stressed that the present work expands on our previous paper (Phillis and Andriantiatsaholiniaina, 2001). The main contribution of this research, aside from refining several points of our past paper, is the introduction of derivatives (gradients) of linguistic variables with respect to indicators. This is a nontrivial task and a necessary step towards using the full decision-making potential of the model. There are indicators whose values are good but they tend towards deterioration. The sensitivity analysis spots such indicators and often provides counterintuitive results necessary to form the full picture of sustainability.

Another point worth mentioning is that, although we provide a lot of explanation about our model, it is bound to remain a "black box" to some extent for the layman. To understand the model fully, one has to be reasonably versed in fuzzy logic and calculus. The software, however, can be used by the layman without difficulty. Knowledge of the inner workings of the model is required if one needs to change the knowledge bases or the membership functions. Our model, however, does not differ in this respect from most others. It is usable by the majority of interested agents but fully understood by the experts.

2. Overview of the SAFE model

2.1. Indicators of sustainable development

Sustainable development, as described by the Brundtland report, is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). Although sustainable development is difficult to define using mathematical terms, many researchers recognize that it is a function of two major components, ecological and human (Pearce and Turner, 1990; Milon and Shogren, 1995; Rauch, 1998). Therefore, sustainable decision-making should have two simultaneous goals:

- achievement of human development to secure high standards of living;
- protection and improvement of the environment now and for the generations to come.

Since the Earth Summit in 1992, an increasing number of researchers and international organizations began to consider "social sustainability", "economic sustainability", "community sustainability", and even "cultural sustainability" as parts of the human dimension of sustainable development (Hardoy et al., 1992;

Pugh, 1996). Thus, sustainable development ought to have environmental, economic, political, social, and cultural dimensions simultaneously (Dunn et al., 1995).

According to the SAFE methodology, the overall sustainability (OSUS) of the system whose development we are asked to appraise has two major dimensions: ecological sustainability (ECOS) and human sustainability (HUMS). These will be referred to as the *primary components* of the overall sustainability. The ecological dimension of sustainability comprises four *secondary components*: water quality (WATER), land integrity (LAND), air quality (AIR), and biodiversity (BIOD). The variables describing the human dimension of sustainability are political aspects (POLIC), economic welfare (WEALTH), health (HEALTH), and education (KNOW). Fig. 1 illustrates all the dependencies of sustainability components.

To evaluate the secondary components, we adopt the Pressure–State–Response approach [Organization for Economic Co-operation and Development (OECD), 1991], which was originally proposed to assess the environmental component of sustainability (see Spangenberg and Bonniot, 1998 for a review and discussion of variants of this approach). Specifically, the SAFE model uses three quantities to describe each secondary component: PRESSURE, STATUS, and RESPONSE, called *tertiary components*. STATUS describes the current overall state of a secondary component we want to assess. It is a function of a number of indicators, which we

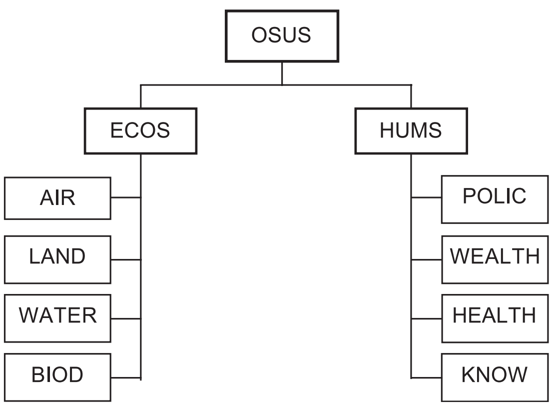

Fig. 1. Dependencies of sustainability components.

call *basic*, because they act as primitives when we compute composite indicators such as PRESSURE, STATUS, RESPONSE, or LAND, WATER, etc. For example, the STATUS of biodiversity is an aggregate measure of the forest area and the numbers of plant, fish, and mammal species per square kilometer. PRESSURE is an aggregate measure of the changing forces human activities exert on the state of the corresponding secondary component. Finally, RESPONSE summarizes the environmental, economic, and social actions taken to bring pressure to a level that might result in a better state.

The indicators used in the SAFE model are given in Table 1 (see Appendix A for definitions of these indicators). Statistical data for the basic indicators can be obtained from many sources, such as United Nations organizations, World Bank, World Resources Institute, international federations, governmental and nongovernmental organizations, etc. Definitions of the four ecosystem components are adopted from IUCN/UNEP/WWF (1991) and those for the four components of human sustainability from UNDP (1990) and Prescott-Allen (1995).

2.2. Fuzzy assessment of sustainable development

Sustainable decision-making involves complex and often ill-defined parameters with a high degree of uncertainty due to incomplete understanding of the underlying issues. The dynamics of any socio–environmental system cannot be described by traditional mathematics because of its inherent complexity and ambiguity. In addition, the concept of sustainability is polymorphous and fraught with subjectivity. It is therefore more appropriate to use fuzzy logic for its assessment. Fuzzy logic is a scientific tool that permits modeling a system without detailed mathematical descriptions using qualitative as well as quantitative data. Computations are done with words, and the knowledge is represented by IF–THEN linguistic rules.

The SAFE model uses a number of relevant knowledge bases to represent the interrelations and principles governing the various indicators and components of sustainability and their contribution to the overall sustainability.

The rules and inputs/outputs of each knowledge base are expressed symbolically in the form of

Table 1
Basic indicators[a] used in the SAFE model

Secondary component	Pressure	Status	Response
LAND	(1) Solid and liquid[b] waste generation (2) Nuclear waste (3) Population density (4) Population growth rate	(5) Domesticated land (6) Current forest	(7) Forest change (8) Clean energy production (9) Nationally protected area (10) Urban households with garbage collection
WATER	(11) Urban per capita water use (12) Freshwater withdrawals	(13–15) Quality of water resources: dissolved oxygen, phosphorus, pH	(16) Reduction of organic pollutants (17) Percentage of urban wastewater treated
BIOD	(18–23) Threatened plant, fish, mammal, bird, amphibian, and reptile species (24) Threatened frontier forest	(6) Current forest	(7) Forest change (25) Protected area
AIR	(26) Greenhouse gas emissions Percentage of ozone depletion[b] Other polluting gas emissions (ozone, NO_x, CO, etc.)[b]	(27–30) Atmospheric concentrations of NO_2, SO_2, total suspended particulates, and lead	(31) Fossil fuel use (8) Clean energy production (32) Public transportation
POLIC	(33) Military spending (34) Murders	(35) Human rights (36) Environmental laws and enforcement (37) Regime (democratic–nondemocratic) (38) GINI index (39) Official development assistance	(40) Government expenditure for social services
WEALTH	(41) GDP implicit deflator (42) Imports (43) Private consumption	(44) Total external debt (45) ICRG risk rating (46) GNP (47) Institutional Investor Credit Rating (48) Resource balance (49) Poor households	(50) GDP growth (51) Exports (52) Central government finance (53) General government consumption
HEALTH	(54,55) Cases of infectious diseases: measles, tuberculosis, AIDS[b], etc. (56) Infant mortality rate (57) Maternal mortality rate	(58) Life expectancy (59–61) Percentage of one-year-old infants immunized against severe diseases: measles, polio, DPT, etc.	(62,63) Number of people per doctor and per nurse (64) Public health expenditure (65) Daily per capita calorie supply (66) Access to sanitation
KNOW	(67–69) Ratio of students to teaching staff (primary, secondary, and tertiary education) (70) Nationals studying abroad	(71,72) Expected years of schooling: male and female (73,74) Net school enrollment: primary and secondary education (75) Number of scientists and engineers involved in research and development	(76) Number of libraries (77) Public expenditure on education (78) Personal computers (79) Internet hosts

[a] Sources and definitions of indicators in Climate Change Secretariat (2000), IHF (2001), OECD (1991, 2000, 2001, 2002), UNESCO (1998), World Bank (1997, 1998, 2000), WRI et al. (1998, 2000), and Loh et al. (1999).
[b] Not taken into account in the examples because of lack of data for selected economies.

words or phrases of a natural language and mathematically as linguistic variables and fuzzy sets. Examples of IF–THEN rules used in the model are:

IF HUMS is *good* AND ECOS is *bad*, THEN OSUS is *average*;

IF LAND is *very bad* OR WATER is *very bad* OR BIOD is *very bad*
OR AIR is *very bad*, THEN ECOS is *very bad*;
IF PRESSURE(LAND) is *average* AND STATUS(LAND) is *good*
AND RESPONSE(LAND) is *bad*, THEN LAND is *average*;

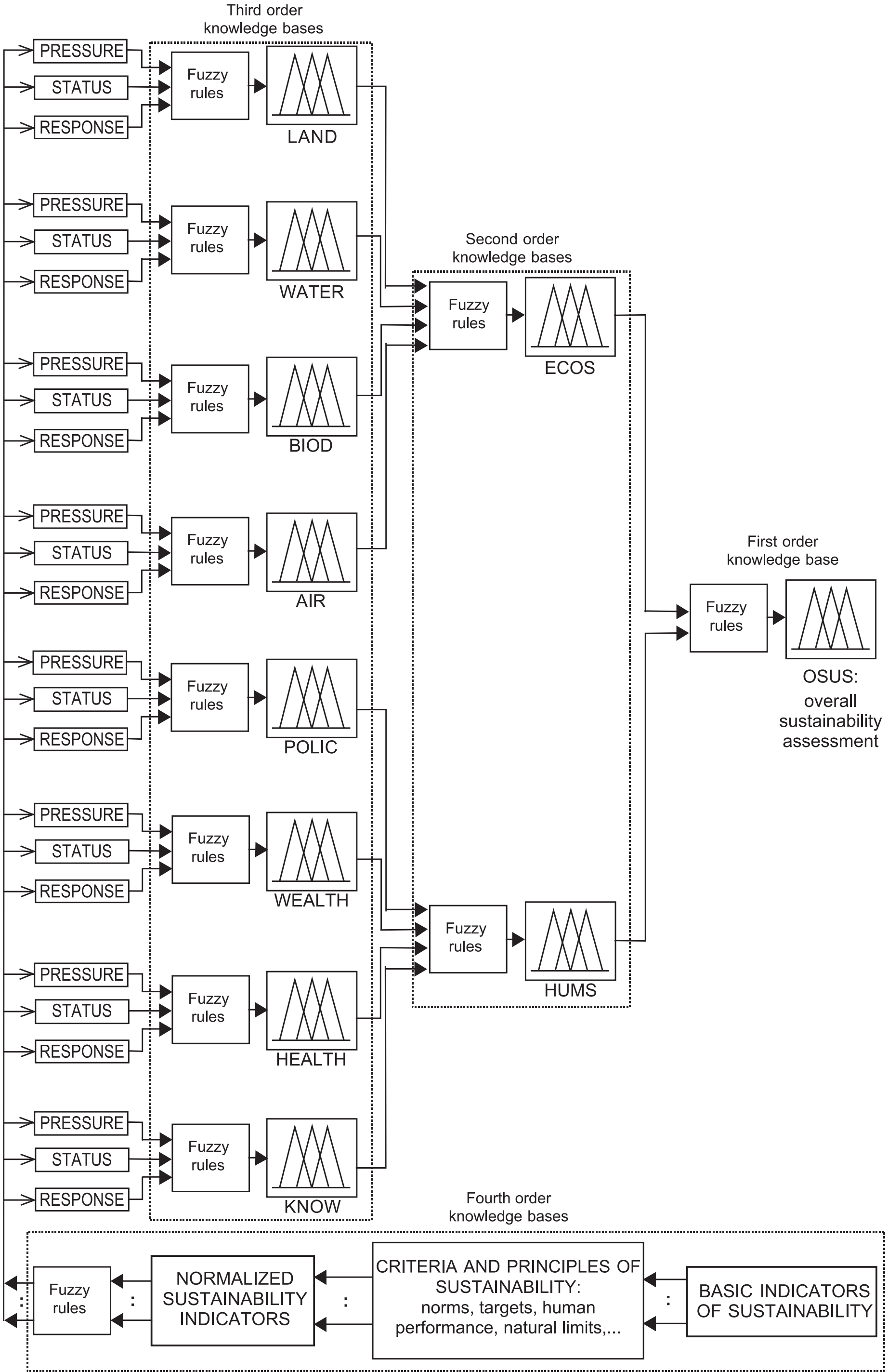

Fig. 2. Configuration of the SAFE model.

IF (Domesticated land) is *medium* AND (Current forest) is *weak*
THEN STATUS(LAND) is *bad*.

The configuration of the SAFE model is shown in Fig. 2. This model may be viewed as a treelike network of knowledge bases. The inputs of each knowledge base are basic indicators provided by the user or composite indicators collected from other knowledge bases. By using fuzzy logic and IF–THEN rules, these inputs are combined to yield a composite indicator as output, which is then passed on to subsequent knowledge bases. For example, the third-order knowledge base that computes the indicator LAND combines PRESSURE, STATUS, and RESPONSE indicators of land integrity which are outputs of fourth-order knowledge bases. Then, LAND is used as input to a second-order knowledge base to assess ECOS. The overall sustainability is obtained from the first-order knowledge base by combining the composite indicators of the primary components of sustainability, ECOS and HUMS.

The model is flexible in the sense that users can choose the set of indicators and adjust the rules of any knowledge base according to their needs and the characteristics of the socio–environmental system to be assessed.

3. Sustainable decision-making using sensitivity analysis

In this section, we attempt to provide an answer to the question of how to achieve sustainability in a manner that could help decision makers to design a rational path towards it.

To be able to design policies for sustainable development, one should have a tool for measuring sustainability and a tool for simulating sustainability scenarios. Without these tools, it is difficult to formulate a policy for sustainable development because not only is there no alternative way to assess the results of the policy, but it is also impossible to tell whether the society is on a sustainable path or not.

The SAFE model provides these prerequisite tools for the formulation of sustainable policies by assessing sustainability for different scenarios of development. A scenario is defined by a suite of sustainability indicators which largely reflect the results of policies and actions taken in a particular period. When these values are changed, and the resulting changes on sustainability were observed, we could identify the most important indicators promoting or impeding progress toward sustainable development. This procedure is known as sensitivity analysis. The next step is to recommend future policies and actions that would increase or decrease the values of the indicators identified as promoting or impeding, respectively.

In this paper, suggestions regarding the values of indicators are restricted to tendency terms ("increase" or "decrease"). Assigning quantitative values is another bigger issue that is not dealt with in this work. This would require the formulation of a constrained optimization problem and is the subject of future research.

Sensitivity analysis plays a fundamental role in decision-making because it determines the effects of a change in a decision parameter on system performance. Additionally, because most decisions regarding sustainable development involve groups of experts, politicians, and individuals, often with uncertain criteria and conflicting interests (Hersh, 1999), sensitivity analysis could be used to investigate the dependencies of sustainability components on particular policies and decisions.

As discussed in Section 2.2, the SAFE system is a treelike network of knowledge bases. Mathematically, any primary component of sustainability (ECOS, HUMS) or the overall sustainability can be expressed as a composition of functions, each of which is a composition of other functions and so on. The key variables involved in this representation are the basic indicators used as inputs in the fourth-order knowledge bases. Sensitivity analysis entails the computation of the gradients (partial derivatives) of ECOS, HUMS, and OSUS with respect to these basic indicators. A derivative gives the increase of sustainability per unit increase of some basic indicator.

Next, we describe a simple method to extract gradient information from the SAFE model. Specifically, we approximate the derivatives of the overall sustainability and its primary components by difference quotients. We show that this approximation yields exact estimates in most cases.

Although each knowledge base has its own rule base and uses different inputs, all knowledge bases are equipped with the following components:

- a normalization module,
- a fuzzification module,
- an inference engine,
- a defuzzification module.

3.1. Normalization

Data of each basic indicator are normalized on a scale between zero (lowest level of sustainability) and one (highest level of sustainability) to allow aggregation and to facilitate fuzzy computations. This is done as follows. To each basic indicator, c, we assign a target, a minimum, $\underline{c}$, and a maximum value $\bar{c}$. The target can be a single value or, in general, any interval on the real line of the form $[t_c, T_c]$ representing a range of desirable values for the indicator. The maximum and minimum values are taken over the set of available measurements of the indicator from various countries or ecosystems. Certain indicators are not comparable in different ecosystems. For example, the number of insect species in Brazil is not comparable to that in Finland. A sensible indicator could be the rate of species percentage that becomes extinct or endangered. Such uses of data should result from consultation with experts.

Let x_c be the indicator value for the system whose sustainability we want to assess. The normalized value, y_c, is calculated as follows

$$y_c(x_c) = \begin{cases} \dfrac{x_c - \underline{c}}{t_c - \underline{c}} & \underline{c} \le x_c < t_c \\ 1 & t_c \le x_c \le T_c \\ \dfrac{\bar{c} - x_c}{\bar{c} - T_c} & T_c < x_c \le \bar{c} \end{cases} \tag{1}$$

From Fig. 3, we see that $y_c(x_c)$ is a trapezoidal function.

The derivative of y_c at x_c, assuming it exists, is the slope of the tangent line of y_c at x_c. Obviously,

$$y'_c(x_c) = \begin{cases} \dfrac{1}{t_c - \underline{c}} & \underline{c} < x_c < t_c \\ 0 & t_c < x_c < T_c \\ -\dfrac{1}{\bar{c} - T_c} & T_c < x_c < \bar{c} \end{cases} \tag{2}$$

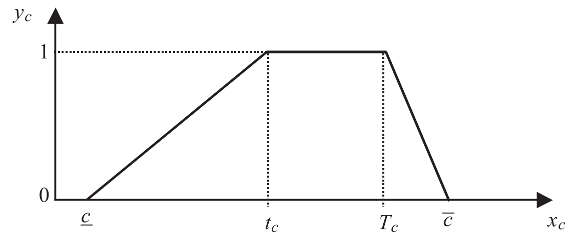

Fig. 3. Normalized value of indicator c.

Note that Eq. (2) does not specify the derivatives of y_c at the points, $\underline{c}$, $\bar{c}$, t_c, and T_c, because they do not exist. The left and right derivatives are

$$y'_c(\underline{c}^+) = \frac{1}{t_c - \underline{c}} \quad y'_c(\underline{c}^-) = 0$$

$$y'_c(\bar{c}^+) = 0 \quad y'_c(\bar{c}^-) = -\frac{1}{\bar{c} - T_c}$$

$$y'_c(t_c^+) = 0 \quad y'_c(t_c^-) = \frac{1}{t_c - \underline{c}}$$

$$y'_c(T_c^+) = -\frac{1}{\bar{c} - T_c} \quad y'_c(T_c^-) = 0$$

In this paper, the derivative of y_c is approximated using the central-difference quotient

$$y'_c(x_c) \cong \frac{y_c(x_c + \delta_c) - y_c(x_c - \delta_c)}{2\delta_c} \tag{3}$$

where δ_c is a small positive number. If δ_c is sufficiently small so that y_c is linear in the interval $[x_c - \delta_c, x_c + \delta_c]$, then the central-difference quotient is equal to the derivative at x_c. This shows that the approximation we adopt provides good estimates of the derivatives of any piecewise linear function. Right and left derivatives can be computed similarly using forward and backward differences, respectively, divided by δ_c (see Appendix B).

In the following subsections, we demonstrate that most of the computations performed in the rule base involve piecewise linear functions which justifies the use of difference quotients to approximate derivatives.

3.2. Fuzzification

The fuzzification module transforms the crisp, normalized value, y_c, of indicator, c, into a linguistic variable in order to make it compatible with the rule base. Loosely speaking, a linguistic variable is a variable whose values are words or phrases. In the model, the linguistic values of each basic indicator are *weak* (W), *medium* (M), and *strong* (S). For composite indicators, we use five linguistic values: *very bad* (VB), *bad* (B), *average* (A), *good* (G), and *very good* (VG).

A linguistic value, LV, is represented by a fuzzy set using a membership function $\mu_{LV}(y)$. The membership function associates with each normalized indicator value, y_c, a number, $\mu_{LV}(y_c)$, in [0, 1] which represents the grade of membership of y_c in LV or, equivalently, the truth value of proposition ''indicator c is LV''. The SAFE model uses trapezoidal and triangular membership functions. An example of defuzzification is shown in Fig. 4 for a hypothetical indicator, c, *with* five linguistic values VB, B, A, G, and VG. The normalized values of c lie on the horizontal axis.

Because all membership functions are trapezoidal, they are piecewise linear. Furthermore, $y_c(x_c)$ is also piecewise linear in x_c. Hence, the derivatives of all these functions can be computed using difference quotients.

3.3. Inference

Each knowledge base in the SAFE model uses IF–THEN rules and approximate reasoning to compute a composite indicator of sustainability from its components expressed as fuzzy (or fuzzified) indicators. In this section, we examine the corresponding computations in detail. Because the membership functions of any composite indicator are piecewise linear, the gradients of these functions can be computed numerically using difference quotients.

membership functions: $\mu_{VB}(y)$, $\mu_B(y)$, $\mu_A(y)$ $\mu_G(y)$, $\mu_{VG}(y)$

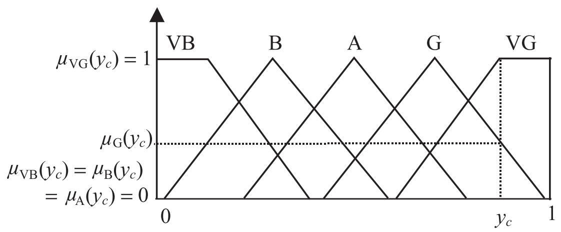

Fig. 4. Examples of linguistic values of indicator c.

We consider a typical knowledge base that computes indicator, s, from a number of input indicators, say, 1, 2, ..., c, ... Suppose that s is represented by the linguistic values, LV_α, LV_β, ..., LV_ν, ... with membership functions, μ_α, μ_β, ..., μ_ν, ..., respectively. Similarly, for the input indicators, the linguistic values are denoted by LV_1, LV_2, ..., LV_k, ... with membership functions μ_1, μ_2, ..., μ_k, ... Finally, for each input indicator, c, the following are available:

y_c—normalized value of c (computed from the data or by some other inference engine), c=1, 2, ...
$\mu_k(y_c)$—grade of membership of y_c in each linguistic value, LV_k, where k=1, 2, ... and c=1, 2, ...

A rule r of the rule base has the form

IF ''indicator 1 is LV_i'' AND(OR) ''indicator 2 is LV_j'' ... AND(OR) ''indicator c is LV_k'' ..., THEN ''indicator s is LV_ν''.

In the model (and in most practical applications), OR is expressed by the max-operator while AND is expressed by the min-operator. Thus, the truth value of the composite proposition

$$\text{PREMISE}_r \triangleq \text{''indicator 1 is } LV_i\text{''}$$
$$\text{AND ''indicator 2 is } LV_j\text{''}\ldots$$
$$\text{AND ''indicator } c \text{ is } LV_k\text{''}\ldots$$

is

$$\mu_{\text{PREMISE}_r} = \min\{\mu_i(y_1), \mu_j(y_2), \ldots, \mu_k(y_c), \ldots\} \quad (4)$$

where $\mu_i(y_1)$, $\mu_j(y_2)$, ... are the truth values of the individual propositions.

Operators max and min preserve piecewise linearity and $\mu_k(y_c)$ is a piecewise linear function of x_c for each $k=i, j$, ... and c=1, 2, ... Therefore, μ_{PREMISE_r} is also a piecewise linear function of (x_1, x_2, ...).

In general, a rule base may contain several rules assigning subsets of the same linguistic value, LV_ν, to indicator s. For example, the rule base of the tertiary component KNOW contains the following rules:

IF PRESSURE is *average* AND STATUS is *good* AND RESPONSE is *very good*, THEN KNOW is *good*.

IF PRESSURE is *bad* AND STATUS is *very good* AND RESPONSE is *very good*, THEN KNOW is *good*.

To combine the results of these rules into a single truth value, we use the union of the individual rule meanings via the max-operator (Driankov et al., 1996). In general, if $R_{s,v}$ is the collection of all rules assigning the linguistic value, LV_v, to indicator, s, the truth value of the conclusion "indicator s is LV_v" is expressed by

$$f_{s,v} = \max_{r \in R_{s,v}} \mu_{\mathrm{PREMISE}_r} \quad (5)$$

If $R_{s,v}$ contains a single rule, say, r, then $f_{s,v}=\mu_{\mathrm{PREMISE}_r}$. Again, one can view $f_{s,v}$ as a function of $(x_1, x_2, \ldots)$ satisfying piecewise linearity. Hence, the partial derivatives $\partial f_{s,v}/\partial x_c$ exist, except at a finite number of points, and can be computed using difference quotients.

Finally, the inference engine produces a single-fuzzy subset, $LV_{s,v}$, for each linguistic value LV_v. The membership function of $LV_{s,v}$ assigns a degree of fulfillment $\mu_{s,v}(z)$ of any numerical value $z \in [0, 1]$ of indicator, s, to the linguistic value, and it is computed from

$$\mu_{s,v}(z) = \min\{\mu_v(z), f_{s,v}\} \quad (6)$$

where $\mu_v(z)$ is the membership function of the original linguistic value LV_v. We observe that $\mu_{s,v}(z)$ has the same shape as $\mu_v(z)$, and it is piecewise linear in $f_{s,v}$. Its maximum value is $f_{s,v}$ which is called the height of the fuzzy set $LV_{s,v}$.

The collection of the heights, $f_{s,v}$, and membership functions, $\mu_{s,v}(z)$, of the fuzzy sets, $LV_{s,v}$, $v=\alpha, \beta, \ldots$, constitutes the output of the inference engine.

3.4. Defuzzification and gradient estimation by central-difference quotients

Defuzzification is the final operation assigning a numerical value in [0, 1] to the composite indicator s. The SAFE model can use center-of-gravity, bisector-of-area, or height defuzzification. In this paper, we use height defuzzification because it has similar properties with the other two methods (see Driankov et al., 1996, for a comparison of various defuzzification methods), but it is simpler and permits expressions of derivatives in closed form (see Appendix B).

Height defuzzification is done as follows. Firstly, we determine the peak value, $p_{s,v}$, of each fuzzy set $LV_{s,v}$, $v=\alpha, \beta, \ldots$. The peak value of any trapezoidal membership function, $\mu_{s,v}(z)$, is the middle point of the closed interval $[l_{s,v}, u_{s,v}]$, such that $\mu_s(l_{s,v})=\mu_s(u_{s,v})=f_{s,v}$ (see Fig. 5). Therefore,

$$p_{s,v} = \frac{l_{s,v} + u_{s,v}}{2} \quad (7)$$

Then, the crisp value of indicator, s, is computed from

$$y_s(x_1, x_2, \ldots) = \frac{\sum_{v=\alpha,\beta,\ldots} p_{s,v} f_{s,v}}{\sum_{v=\alpha,\beta,\ldots} f_{s,v}}. \quad (8)$$

The above procedure is illustrated in Fig. 5 for a hypothetical indicator, s, with two linguistic values, LV_α and LV_β, and heights $f_{s,\alpha}=0.5$ and $f_{s,\beta}=0.7$. By applying Eq. (8), we obtain $y_s=(0.2\times0.5+0.8\times0.7)/(0.5+0.7)=0.66/1.2=0.55$.

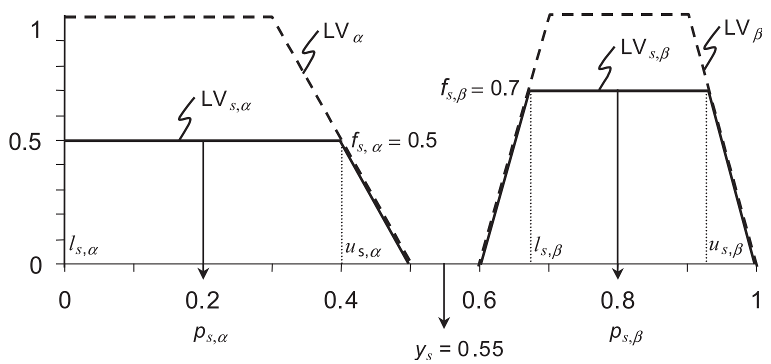

Fig. 5. Illustration of height defuzzification.

In sensitivity analysis, we use difference quotients to approximate partial derivatives. All calculations involving the various components of sustainability, $y_s(x_1, x_2, \ldots)$, and their sensitivities to the basic indicators are done using MATLAB's Simulink toolbox (The MathWorks, 1995). We also have developed a more efficient program in Fortran 77 code which requires less CPU time and can use height defuzzification (MATLAB does not support height defuzzification). The central-difference quotient of a component, s, of sustainability with respect to an indicator, c, is computed from

$$\frac{y_s(x_1, x_2, \ldots, \bar{x}_c, \ldots) - y_s(x_1, x_2, \ldots, \underline{x}_c, \ldots)}{\bar{x}_c - \underline{x}_c}$$

where $\bar{x}_c$ and $\underline{x}_c$ are two values around x_c. Forward- and backward-difference quotients are computed similarly (see Appendix B). Because the basic indicators have different ranges of values, we scale these quotients so that they represent the effect of a 1% increase of each indicator on sustainability. This permits a fair comparison of indicators. We see that

$$\begin{aligned}&\frac{y_s(x_1, x_2, \ldots, \bar{x}_c, \ldots) - y_s(x_1, x_2, \ldots, \underline{x}_c, \ldots)}{\bar{x}_c - \underline{x}_c}\\ &= \frac{\text{effect on } s \text{ of a } (\bar{x}_c - \underline{x}_c) \text{ increase } of\ c}{(\bar{x}_c - \underline{x}_c)}\\ &\cong \frac{\text{effect on } s \text{ of a } 1\% \text{ increase of } c}{(\bar{c} - \underline{c}) \times 1/100}\end{aligned}$$

where $\bar{c}$ and $\underline{c}$ are the maximum and minimum values of indicator c. Thus, the sensitivity of component, s, to indicator, c, is defined by

$$\Delta_s^{(c)} = \frac{y_s(x_1, x_2, \ldots, \bar{x}_c, \ldots) - y_s(x_1, x_2, \ldots, \underline{x}_c, \ldots)}{\bar{x}_c - \underline{x}_c} \times \frac{(\bar{c} - \underline{c})}{100} \qquad (9)$$

In the SAFE model, we set $\bar{x}_c = x_c + \delta_c$, $\underline{x}_c = x_c - \delta_c$, and $\delta_c = \varepsilon\ (\bar{c} - \underline{c})$, where ε is a small positive scale factor.

For small values of ε, the sensitivity to a specific indicator may be zero. This is so because the SAFE model uses max- and min-operators which ignore most of the input values when sustainability is assessed and, therefore, the partial derivatives of y_s may be zero for most of the input values and nonzero for just a few of them. By using difference quotients, the results of sensitivity analysis are richer than those obtained by derivatives because the values, y_s, are more sensitive to finite perturbations than to infinitesimal ones.

In summary, sensitivity analysis is done in the following steps:

1. Input the values of basic indicators, say, $1, 2, \ldots, c, \ldots$ to the SAFE model. Specify a scale factor, ε, and compute the magnitude, $\delta_c = \varepsilon\ (\bar{c} - \underline{c})$, of perturbation of each indicator value x_c. Truncate perturbations, if necessary: set $\bar{x}_c = \min(x_c + \delta_c,\ \bar{c})$ and $\underline{x}_c = \max(x_c - \delta_c,\ \underline{c})$.
2. For each primary component and the overall sustainability, s=ECOS, HUMS, OSUS:
   (i) invoke the SAFE model to compute $y_s(x_1, x_2, \ldots, x_c, \ldots)$;
   (ii) for each basic indicator, c, compute:
   $y_s(x_1, x_2, \ldots, \bar{x}_c, \ldots)$;
   $y_s(x_1, x_2, \ldots, \underline{x}_c, \ldots)$;
   and the sensitivity, $\Delta_s^{(c)}$, from Eq. (9).

A numerical example illustrating the above algorithm and some remarks on sensitivity analysis are given in Appendix B.

4. Application of the SAFE model to sustainable decision-making

We now provide some examples illustrating the application of sensitivity analysis to support sustainable decision-making. Sensitivity analysis pinpoints those parameters that affect sustainability critically (e.g., clean energy production, renewable water resources, etc.). Policy makers then should take proper corrective actions in these critical directions. We examine two countries (Greece and USA) and compute the primary components of sustainability and their sensitivities to various input indicators. We make the following remarks:

1. If the derivative with respect to a basic indicator is negative, then we classify this indicator as *impeding* because an increase of its value will reduce the degree of sustainability.

2. If the derivative is positive, then the indicator is classified as *promoting* because an increase in its value will lead to higher sustainability. Impeding and promoting indicators are crucial in establishing the best practices towards sustainability.
3. When the derivative is zero, the indicator is classified as *neutral* and policy makers could ignore it when recommending short-term policies.

According to the results of sensitivity analysis and the target for each indicator, we may design policies to advance ecological, human, and overall sustainability by

- proposing mechanisms and projects to improve promoting indicators or maintain them, if their values are optimal,
- taking precautionary measures to correct impeding indicators or maintain them, if their values are optimal, and
- adopting conservative actions for neutral indicators.

In a previous paper (Phillis and Andriantiatsaholiniaina, 2001), we used about 50 basic indicators to assess the sustainability of 15 selected countries. The results showed that all economies were unsustainable. As the flexibility of the model permits the use of more indicators, in this paper, we use 79 indicators and perform sensitivity analysis in order to evaluate strategies for sustainable development. We restrict our attention to just two economies, Greece and USA, because of the availability of data and authors' personal knowledge of the prevailing political and social conditions in these two countries. The latter is very important because the SAFE model takes into account subjective evaluations concerning human rights, democracy, law enforcement, etc.

The results of sustainability assessment are given in Table 2. The values range from zero (worst value) to one (best value). Details about the selection of indicators used in the model can be found in Phillis and Andriantiatsaholiniaina (2001).

The numerical results of our previous work (Table 5 in Phillis and Andriantiatsaholiniaina, 2001) differ from Table 2 by 0–40%. This discrepancy is due to revising our data and a fine-tuning of the rule bases, which we performed in the present paper by consulting with experts. However, our main objective is the presentation of the model.

Table 2
Overall development sustainability measurements for Greece and USA in 1990–1999

Components of sustainability	Greece	USA
LAND	0.49	0.50
WATER	0.85	0.70
BIOD	0.30	0.40
AIR	0.30	0.63
ECOS	0.44	0.50
POLIC	0.38	0.50
WEALTH	0.49	0.56
HEALTH	0.70	0.71
KNOW	0.50	0.90
HUMS	0.48	0.56
Overall sustainability (OSUS)	0.444	0.564

To achieve sustainable development, a balanced and continuing improvement of the four components of ECOS (LAND, WATER, BIOD, AIR) and the four components of HUMS (POLIC, WEALTH, HEALTH, KNOW) is needed. Thus, a prerequisite for promoting overall sustainability is the detection of critical indicators that affect the value of ECOS, HUMS, and OSUS, or influence the value of LAND, WATER, BIOD, AIR, POLIC, WEALTH, HEALTH, and KNOW.

In general, policy makers should be able to identify the factors that promote or impede progress towards sustainability and obtain quantitative information about them. Each sustainability variable is a function of a number of basic indicators. Thus, for a given country or ecosystem, sustainable decisions should be based on assessments concerning the contribution of each indicator to the final value of ECOS, HUMS, and OSUS. Using these assessments, policy makers could set priorities for critical (promoting or impeding) indicators on which future policies should focus. Of course, decision makers have a multitude of considerations to make before they decide on a strategy such as availability of resources, money and people, political priorities, etc. Here, we provide the point of view of sustainability priority.

Tables 3 and 4 show the results of sensitivity analysis for Greece and USA using ε=0.15 which yields perturbations $\pm$15% around the nominal indicator values. As discussed in Section 3.4, the results

Table 3
Sensitivity analysis of ecological and overall sustainability for selected countries

Basic indicator c	Description	Sensitivities of primary sustainability variables to 1% increase of c			
		Greece		USA	
		Overall sustainability $\Delta_{\mathrm{OSUS}}^{(c)}$	Ecological sustainability $\Delta_{\mathrm{ECOS}}^{(c)}$	Overall sustainability $\Delta_{\mathrm{OSUS}}^{(c)}$	Ecological sustainability $\Delta_{\mathrm{ECOS}}^{(c)}$
LAND					
1	Solid waste generation	−0.00078	−0.00078	0.00000	0.00000
3	Population density	−0.00078	−0.00078	0.00000	0.00000
4	Population growth rate	0.00000	0.00000	−0.00262	−0.00254
5	Domesticated land	0.00000	0.00000	0.00272	0.00266
6	Current forest	0.00000	0.00000	0.00344	0.00330
7	Forest change	0.00180	0.00180	0.00010	0.00011
10	Urban garbage collection	0.00078	0.00078	0.00000	0.00000
WATER					
11	Urban per capita water use	−0.00318	−0.00318	−0.00202	−0.00202
12	Freshwater withdrawals	−0.00131	−0.00159	−0.00262	−0.00258
14	Phosphorus concentration	−0.00479	−0.00479	−0.00262	−0.00254
15	pH	−0.00610	−0.00638	−0.00262	−0.00254
16	Organic pollutants	−0.00252	−0.00252	−0.00262	−0.00254
17	Urban wastewater treated	0.00479	0.00479	0.00262	0.00254
AIR					
26	Greenhouse gas emissions	−0.00131	−0.00159	0.00000	0.00000
27	NO_2 concentration	−0.00479	−0.00479	0.00000	0.00000
28	SO_2 concentration	−0.00479	−0.00479	−0.00221	−0.00219
29	TSP concentration	0.00000	0.00000	−0.00221	−0.00219

are scaled so that they represent the effect of a 1% increase of each indicator on sustainability. Neutral indicators for both countries are omitted for reasons of brevity.

Broadly speaking, sustainable policies should focus on the ecological and human system. On the other hand, there is no unique path towards sustainability, and policy makers should choose different strategies in different countries. To see this, we collect the promoting and impeding indicators for Greece and the USA, and rank them in decreasing order of gradient magnitude.

According to the SAFE sensitivity results, sustainable policies (for both ecological and human system) in Greece depend on enhancing the following promoting factors ranked in order of importance:

(17) Urban wastewater treated;
(7) Forest change, (50) Gross Domestic Product (GDP) growth, (52) Central government finance, and (53) General government consumption;
(10) Urban garbage collection; and
(48) Resource balance;

and decreasing the following impeding factors:

(15) pH;
(14) Phosphorus, (27) NO_2, and (28) SO_2 concentrations;
(11) Urban per capita water use;
(16) Organic pollutants;
(44) Total external debt and (41) GDP implicit deflator;
(26) Greenhouse gas emissions and (12) Freshwater withdrawals;
(3) Population density and (1) Solid waste generation; and
(35) Military spending.

The critical sustainability factors for Greece are environmental, namely, quality and quantity of freshwater resources, air quality, and land protection.

Table 4
Sensitivity analysis of human and overall sustainability for selected countries

Basic indicator c	Description	Sensitivities of primary sustainability variables to 1% increase of c			
		Greece		USA	
		Overall sustainability $\Delta^{(c)}_{OSUS}$	Human sustainability $\Delta^{(c)}_{ECOS}$	Overall sustainability $\Delta^{(c)}_{OSUS}$	Human sustainability $\Delta^{(c)}_{ECOS}$
POLIC					
35	Military spending	0.00000	−0.00053	0.00000	0.00000
40	Government expenditure for social services	0.00000	0.00049	0.00077	0.00073
WEALTH					
41	GDP implicit deflator	−0.00184	−0.00332	−0.00048	−0.00045
43	Private consumption	0.00000	0.00000	−0.00347	−0.00388
44	Total external debt	−0.00184	−0.00332	−0.00048	−0.00045
47	ICRG risk rating	0.00000	0.00000	0.00048	0.00045
48	Resource balance	0.00050	0.00173	0.00340	0.00377
49	Poor households	0.00000	0.00000	−0.00489	−0.00507
50	GDP growth	0.00184	0.00332	0.00000	0.00000
52	Central government finance	0.00184	0.00384	0.00000	0.00000
53	General government consumption	0.00184	0.00332	0.00000	0.00000
HEALTH					
64	Public health expenditure	0.00000	0.00000	0.00142	0.00183
65	Daily per capita calorie supply	0.00000	0.00000	−0.00142	−0.00183

Economical factors, such as financial deficit and government consumption, also play a role.

Sustainable policies for the USA should focus on enhancing the following promoting factors:

(6) Current forest;
(48) Resource balance;
(5) Domesticated land;
(17) Urban wastewater treated;
(64) Public health expenditure;
(40) Government total expenditure for social services;
(47) ICRG risk rating; and
(7) Forest change

and decreasing the following impeding factors:

(49) Poor households;
(43) Private consumption;
(15) pH, (14) Phosphorus concentration, (16) Organic pollutants, (12) Freshwater withdrawals, and (4) Population growth rate;
(28) SO_2 and (29) TSP concentrations;
(11) Urban per capita water use;
(65) Daily per capita calorie supply; and
(44) Total external debt and (41) GDP implicit deflator.

Thus, the critical factors of sustainable development in the USA are environmental and socioeconomical, namely, land protection, water system sustainability, poor households, and resource balance.

Fig. 6 shows the diagrams of derivatives of ecological, human, and overall sustainability for Greece and the USA. These figures can be regarded as ‘‘cardiograms’’ of sustainability, where positive disturbances (peaks) should be pursued through appropriate action, whereas negative ones (dips) must be avoided. Policies ought to respond to such disturbances. It is interesting to observe that the impact of critical factors affecting overall sustainability is heavier for the Greek society than for USA, which means that the latter is more sustainable than the former.

A final remark concerns the usefulness of sensitivity analysis. Because overall sustainability is high when the normalized values of basic indicators are close to one (the target value), a seemingly neat policy for sustainable progress could be to improve first

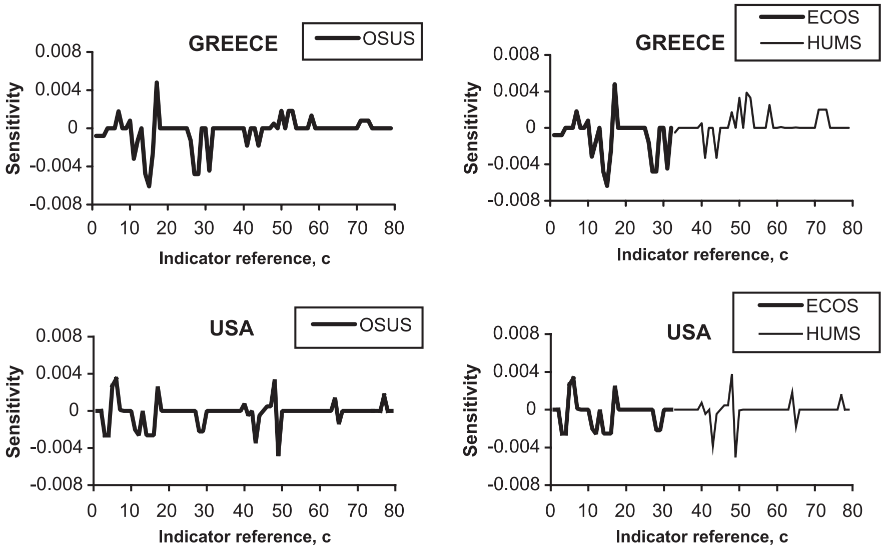

Fig. 6. Sensitivities of sustainability components for Greece and USA.

those indicators whose normalized values are close to zero. However, this policy will not necessarily lead to a maximum increase of sustainability. For example, according to sensitivity analysis, the most important indicator for Greece is water acidity (15, pH) whose normalized value is 0.88, whereas greenhouse gas emissions (26) with a normalized value 0.29 is ranked 15th of the 18 critical indicators.

5. Conclusions

Policy makers need a tool based on scientific information to forecast the effects of future actions on sustainability and establish policies for sustainable development.

In this paper, we use a previously developed model, called SAFE, in an attempt to provide an explicit and comprehensive description of the concept of sustainability. Using linguistic variables and linguistic rules, the model gives quantitative measures of human and ecological sustainability which are then combined into overall sustainability. A sensitivity analysis of the SAFE model permits to determine the evolution of sustainability variables subject to perturbations in the values of basic indicators. Then, the problem of sustainable decision-making becomes one of specifying priorities among basic indicators and designing appropriate policies that will guarantee sustainable progress.

Successful policies differ from country to country. More developed countries need to focus mostly on the degradation of their environment, whereas less developed countries should strive to improve both the environment and the human system.

The SAFE approach provides new insights of sustainable development, and it may serve as a practical tool for decision-making and policy design at the local or regional levels. Such approaches are urgently needed nowadays if we want to attack the problem of sustainable development systematically.

Acknowledgements

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Appendix A. Explanations of indicators and remarks on principles of sustainability

Definitions of indicators are taken from Climate Change Secretariat (2000), International Helsinki Federation for Human Rights (IHF, 2001), OECD (1991, 2000, 2001, 2002), United Nations Educational, Scientific and Cultural Organization (UNESCO, 1998), World Bank (1997, 1998, 2000), World Resources Institute (WRI) et al. (1998, 2000), and Loh et al. (1999).

A.1. LAND indicators

(1) *Solid and liquid waste generation* (kilograms per day and capita): Includes organic, chemical, and physical wastes. Reducing waste generation improves land sustainability. In this work, we have used only data about urban solid waste generation.

(2) *Nuclear waste* (tons of heavy metal per year and thousand people): It is assumed that nuclear energy production influences land sustainability negatively due mainly to generation of heavy metal.

(3) *Population density* (per square kilometer): Obtained from the midyear population number divided by the land area. Land area is total area, excluding inland bodies of water, coastal waterways, and offshore territorial waters. It is assumed that high population density exerts stress on land sustainability.

(4) *Population growth rate* (percentage): Average annual exponential rate of population change for given periods of years. Small or zero population growth rate is perceived as influencing positively land sustainability but not always.

(5) *Domesticated land* (percent of land area): Includes cropland (land for temporary and permanent crops, temporary meadows, market and kitchen gardens, and temporary fallow land) and permanent pasture area (cropland that does not need to be replanted after each harvest, such as cocoa, coffee, fruit trees, rubber, and vines), which maintain land sustainability.

(6) *Current forest* (percent of original): Closed forest cover within the last 10 years or so. Original forest refers to an estimate of land that would have been covered by closed forest about 8000 years ago assuming current climatic conditions before large-scale disturbance by human society began. Forests maintain land sustainability.

(7) *Forest change* (percent of current): Average annual increase or decrease (if negative) of forest cover between 1990 and 1995. Because current forest (6) is less than 100% for all countries, a positive forest change improves land sustainability.

(8) *Clean energy production* (percent of total energy production): Increasing energy sources, such as wind, solar, geothermal and hydroelectric, improves land sustainability. Clean energy does not include nuclear energy.

(9) *Nationally protected area* (percent of total land area): Totally or partially protected area of at least 1000 ha that are designated as national parks, natural monuments, nature reserves, wildlife sanctuaries, protected landscapes and seascapes, or scientific reserves with limited public access to secure land sustainability and environmental functions such as carbon and waste assimilation.

(10) *Urban households with garbage collection* (percentage): Regular waste collection including household collection, regular "dump master" group collection, but not local dumps to which household must carry garbage. Reducing uncontrolled waste improves land sustainability.

A.2. WATER indicators

(11) *Urban per capita water use*: Average consumption of water in liters per person per day for domestic use. Excessive use of water reduces water sustainability.

(12) *Freshwater withdrawals*: Gross freshwater abstractions as percentage of total available water resources (including inflows from neighboring countries).

(13–15) *Quality of water resources*: Improvement in water quality over a given period, measured by dissolved oxygen (13) and phosphorus (14) concentrations, which track eutrophication levels, and pH (15).

(16) *Reduction of water pollutants*: Decrease or increase (if negative) of emissions of organic pollutants between 1990 and 1995 measured in kilograms of biological oxygen demand per cubic kilometer of water. Reducing water pollutants improves water sustainability.

(17) *Urban wastewater treated*: Percentage of all wastewater undergoing any form of treatment, including primary physical and mechanical processes that remove 20–30% of biological demand, secondary additional use of biological treatments that removes 80–90% of biological demand, and tertiary advanced added chemical treatments that remove 95% or more

of biological demand. Treatment of wastewater improves water sustainability.

A.3. BIOD indicators

(18–23) *Threatened plant* (18), *fish* (19), *mammal* (20), *bird* (21), *amphibian* (22), *and reptile* (23) *species* (percentage): Includes all species that are critically endangered, endangered, or vulnerable, but excludes introduced species, species whose status is insufficiently known, those known to be extinct, and those for which a status has not been assessed.

(24) *Threatened frontier forests*: Frontier forests where ongoing or planned human activities, such as logging, mining, and other large-scale disturbances, will eventually degrade the ecosystem through species decline or extinction, drastic changes in the forest's age structure, etc.

(6) *Current forest* (percent of original): Forests maintain biodiversity.

(7) *Forest change* (percent of current): Because current forest (6) is less than 100% for all countries, a positive forest change improves biodiversity.

(25) *Protected area* (percent protected): Forest areas that fall within the protected areas in the world that are listed as the World Conservation Union (IUCN) management categories I–V (WRI et al., 1998). Category I: Scientific reserves and strict nature reserves possess outstanding representative ecosystems. Public access is generally limited with only scientific research and educational use permitted. Category II: National parks and provincial parks are relatively large areas of national or international significance not materially altered by humans. Visitors may use them for recreation and study. Category III: Natural monuments and natural landmarks contain unique geological formations, special animals or plants, or unusual habitats. Category IV: Managed nature reserves and wildlife sanctuaries are protected for specific purposes such as conservation of significant plant or animal species. Category V: Protected landscapes and seascapes may be entirely natural or provincially protected sites, or privately owned areas.

A.4. AIR indicators

(26) *Greenhouse gas emissions* (percentage): Measures deviations from targets of the six gases addressed by the Kyoto Protocol: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), HFCs, PFCs, and sulphur hexafluoride (SF_6). Expressed as CO_2 equivalents.

(27–30) *Atmospheric concentrations of NO_2* (27), *SO_2* (28), *total suspended particulates* (29), *and lead* (30) ($\mu g/m^3$): Current concentrations are compared with 1990 levels in assessing air sustainability.

(31) *Fossil fuel use* (percent of total energy production): Current consumption is compared with 1990 levels. Fossil fuels or traditional fuels include estimates of the consumption of fuel wood, charcoal, bagasse, and animal and vegetal wastes. Reducing fossil fuel use reduces CO_2 emissions.

(8) *Clean energy production* (percent of total energy production): Maximizing clean electricity production improves air quality.

(32) *Public transportation* (percent of work trips by public transport): Measures trips to work made by bus, tram, or train. Bus or minibus includes road vehicles other than cars taking passengers on a fare-paying basis. It does not include other means of transport commonly used in developing countries such as ferry, taxi, animal or rickshaw. Public transportation reduces total CO_2 emissions.

A.5. POLIC indicators

(33) *Military spending* [percent of Gross Domestic Product (GDP)]: For members of the North Atlantic Treaty Organization (NATO), it is based on the NATO definition which covers military-related expenditures of the defense ministry and other ministries. Civilian-type expenditures of the defense ministry are excluded. Military assistance is included in the expenditure of the donor country. Purchases of military equipment on credit are recorded at the time the debt is incurred, not at the time of payment. Data for other countries generally cover expenditure of the ministry of defense; excluded are expenditures on public order and safety which are classified separately.

(34) *Murders* (per 100,000 people): Reported figures on crime may be underreported.

(35) *Human rights*: Subjective assessment of human rights ranging from zero to one, based on the 2001 report of the International Helsinki Federation for Human Rights (IHF) for each country and the

personal knowledge of the authors. This assessment focuses on freedom of expression; ill treatment and misconduct by law enforcement officials, conditions in prisons and detention facilities, racism and anti-Semitism, religious intolerance, protection of national and ethnic minorities, citizenship and statelessness, death penalty, etc.

(36) *Environmental laws and enforcement*: Measurement ranging from zero to one that is obtained by a subjective assessment on the basis of various world reports and authors' knowledge. Convention on biological diversity; Ramsar convention on wetlands of international importance; Convention on International Trade of Endangered Species (CITES) of Wild Fauna and Flora; national environmental laws; etc.

(37) *Regime* (democratic/nondemocratic): Fuzzy subjective measurement of the state of the regime based on the report of the International Helsinki Federation for Human Rights and the knowledge of the authors. Measurements range from perfect democratic (ideal regime with measurement equal to one) to fully nondemocratic regime (dictatorial with measurement equal to zero).

(38) *GINI index*: Measures the extent to which the distribution of income among individuals or households within an economy deviates from a perfectly equal distribution. A GINI index of zero would represent perfect equality and an index of 100 would imply perfect inequality—a single person or household accounting for all income or consumption.

(39) *Official development assistance* (dollars per capita): Consists of disbursements of loans (net repayments of principal) and grants made on concessionary terms by official agencies of the members of the Development Assistance Committee (DAC) and certain Arab countries to promote economic development and welfare in recipient economies listed by DAC as developing. The data do not distinguish among different types of aid (program, project, or food aid; emergency assistance; peacekeeping assistance; or technical cooperation); each of which may have a very different effect on the economy but tends to regulate political sustainability.

(40) *Government expenditure for social services* (percent of GDP): Comprises all government payments in exchange for goods and services, including wages and salaries. Many expenditures relevant to environmental protection, such as pollution abatement, water supply, sanitation, and refuse collection, are included indistinguishably in this category. Low social expenditure is conceived as having negative effects on policy sustainability.

A.6. WEALTH indicators

(41) *GDP implicit deflator* (average annual percentage growth rates): Reflects changes in prices for all final demand categories, such as government consumption, capital formation, and international rate, as well as the main component, private final consumption. It is derived as the ratio of current to constant-price GDP. It is known as the inflation indicator affecting the sustainability of a national economy.

(42) *Imports* (million dollars per capita): Shows the cost plus insurance and freight value in U.S. dollars of goods purchased from the rest of the world.

(43) *Private consumption* (percent of GDP): Market value of all goods and services, including durable products, purchased or received as income in kind by households and nonprofit institutions. In practice, it may include any statistical discrepancy in the use of resources relative to the supply of resources. It is often estimated as a residual by subtracting from GDP all other known expenditures. High private consumption may weaken long-term sustainability.

(44) *Present value of external debt* [percent of Gross National Product (GNP)]: Debt owed to nonresidents repayable in foreign currency, goods, or services. It is the sum of public, publicly guaranteed, and private nonguaranteed long-term debt, use of IMF credit, and short-term debt. The present value of external debt provides a measure of future debt service obligation that can be compared with such indicator as GNP.

(45) *ICRG risk rating*: An overall index taken from the International Country Risk Guide (ICRG); the ICRG collects information on 22 components of risk, groups these components into three major categories (political, financial, and economic), and calculates a single-risk assessment index ranging from 0 to 100. Ratings below 50 indicate very high risk, and those above 80 indicate very low risks.

(46) *GNP per capita* (dollars per capita): GNP is the sum of two components: GDP and net income from abroad. Net income from abroad is income in the form of compensation of employees, interests on loans, profits, and other factor payments that residents receive from abroad. GDP measures the final output of goods and services produced by the domestic economy. This indicator is commonly used to evaluate the status of wealth sustainability on the national level.

(47) *Institutional investor credit ranking*: Ranks, on a scale from 0 to 100, the probability of a country's default. A high number indicates a low probability of default on external obligations. Institutional investor country credit ratings are based on information provided by leading international banks. Risk ratings may be highly subjective, reflecting external perceptions that do not always capture a country's actual situation. But these subjective perceptions are the reality that policymakers face in the climate they create for foreign private inflows.

(48) *Resource balance* (percent of GDP): This indicator provides the difference between exports of goods/services and imports of goods/services for each country.

(49) *Poor households*: Percentage of population living below the national poverty line. National estimates are based on population-weighted subgroup estimates from household surveys. Reducing poor households improves wealth sustainability.

(50) *Average annual growth rate of GDP* (percent per year): Calculated from constant-price GNP and GDP in national currency units.

(51) *Exports* (million dollars per capita): Shows the free on-board value, in U.S. dollars, of goods provided to the rest of the world. Increasing export balances import and maintains wealth sustainability.

(52) *Central government finance*: Overall deficit (−) or surplus (+) in percentage of GDP, current and capital revenue and official grants received, less total expenditure and lending minus repayment.

(53) *General government consumption* (percent of GDP): Includes all current spending for purchases of goods and services (including wages and salaries) by all levels of government, excluding most government enterprises. It also includes most expenditure on national defense and security, some of which is now considered part of investment.

A.7. HEALTH indicators

(54,55) *Cases of infectious diseases*: Measles (54) and tuberculosis (55) per million people. Data are based on official reports from countries to the World Health Organization (WHO) regional offices as well as on reports from scientific literature and qualified laboratories.

(56) *Infant mortality rate*: Number of infants who die before reaching 1 year of age, expressed per 1000 live births in a given year.

(57) *Maternal mortality rate*: Annual number of deaths from pregnancy or childbirth-related causes per 100,000 live births. A maternal death is defined by WHO as the death of woman while pregnant or within 42 days of the termination of pregnancy from any cause related to or aggravated by the pregnancy including abortion.

(58) *Life expectancy*: Number of years a newborn infant would live if patterns of mortality prevailing at the time of its birth were to stay the same throughout its life. Life expectancy reflects the sustainability of a health system.

(59–61) *Infants immunized against severe diseases*: Percentage of one-year-old infants immunized against measles (59), polio (60), and diphtheria–pertussis–tetanus (DPT) (61).

(62,63) *Number of people per doctor* (62) *and per nurse* (63): Refers to data mainly from WHO's second evaluation of progress in implementing national health-for-all strategies. Data for developing countries are supplemented by country statistical yearbooks and by World Bank sector studies. Doctors are defined as graduates of any faculty or school of medicine. Nurses are persons who have completed a program of basic nursing education.

(64) *Public health expenditure* (percentage of GDP): Consists of recurrent and capital spending from government budgets, external borrowings and grants, and social health insurance.

(65) *Daily per capita calorie supply* (percentage of total requirements): Data taken from the Food and Agricultural Organization (FAO) food balance sheets. The calories and protein actually consumed may be lower than the figure shown, depending on how much is lost during home storage, preparation, and cooking, and how much is fed to pets and domestic animals or discarded.

(66) *Access to sanitation*: Percentage of population with at least adequate disposal facilities that can effectively prevent human, animal, and insect contact with excreta. Suitable facilities range from simple but protected pit latrines to flush toilets with sewerage. To be effective, all facilities must be correctly constructed and properly maintained.

A.8. KNOW indicators

(67–69) *Ratio of students to teaching staff [primary* (67), *secondary* (68), *and tertiary* (69) *education)*: Teaching staff includes (OECD, 2000) professional personnel involved in direct student instruction: classroom teachers, special education teachers, other teachers who work with students as a whole class, chairpersons of departments; it does not include nonprofessional personnel who support teachers.

(70) *Nationals studying abroad*: Estimated number of students studying abroad as proportion of total enrolment. The data suggest that the less developed countries account for most of the students who study abroad (UNESCO, 1998). Export of students may influence knowledge sustainability negatively.

(71,72) *Expected years of schooling; male* (71) *and female* (72): Average number of years of formal schooling that a child is expected to receive including university education and years spent in repetition. It may also be interpreted as an indicator of the total educational resources, measured in school years, that a child will require over the course of schooling.

(73,74) *Net school enrollment ratio; primary* (73) *and secondary* (74): Number of children of official school age, as defined by the education system, enrolled in primary or secondary school, expressed as percentage of the total number of children of that age (World Bank, 2000).

(75) *Number of scientists and engineers in research and development (R&D)*: Number of people trained to work in any field of science who are engaged in professional research and development (R&D) activity, including administrators, per million people. Most such jobs require completion of tertiary education. Increasing the number of scientists and engineers improves knowledge sustainability.

(76) *Number of libraries* (per capita): Libraries serving the population of a community or region free of charge or for a nominal fee; they may service the general public or special categories of users such as children, members of the armed forces, hospital patients, prisoners, workers, and employees. United Nations Education, Scientific, and Cultural Organization (UNESCO) counts libraries in numbers of administrative units and service points. An administrative unit is any independent library or group of libraries under a single director or a single administrator; a service point is any library that provides in separate quarters a service for users, whether it is an independent library or a part of a larger administrative unit.

(77) *Public expenditure on education*: Percentage of GNP accounted for by public spending on public education plus subsidies to private education at the primary, secondary, and tertiary levels. It may exclude spending by religious schools which play a significant role in many developing countries. Data for some countries and for some years refer to spending by the ministry of education of the central government only, and thus exclude education expenditures by other central government ministries and departments, local authorities, and others.

(78) *Personal computers* (per thousand people): Estimated numbers of self-contained computers used by a single person. Access to personal computers promotes knowledge development and educational sustainability.

(79) *Internet hosts*: Number of computers directly connected to the worldwide network of interconnected computer systems per 10,000 people. Access to the Internet facilitates knowledge acquisition.

Appendix B. Illustration of fuzzy computations and some remarks on sensitivity analysis

We present a numerical example illustrating how the SAFE model assesses sustainability and performs sensitivity analysis. Consider the secondary variable KNOW and its components PRESSURE (PR), STATUS (ST), and RESPONSE (RE). For simplicity, we use only three fuzzy sets, *weak* (W), *medium* (M), and *strong* (S), to represent the tertiary variables (Fig. 7.) and five fuzzy sets for KNOW, *very bad* (VB), *bad* (B), *average* (A), *good* (G), and *very good* (VG). Table 5 shows the corresponding rule base which consists of 3^3=27 rules.

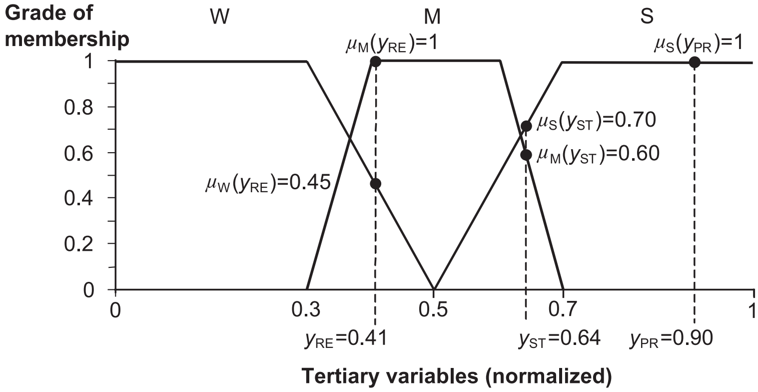

Fig. 7. Linguistic values and fuzzification of crisp inputs.

Suppose that information concerning the tertiary variables is expressed numerically as follows: PRESSURE has the value y_{PR}=0.90; STATUS has the value y_{ST}=0.64; and RESPONSE has the value y_{RE}=0.41. Fuzzification (see Fig. 7) yields the following inputs of the inference engine:

Input 1: PRESSURE is *strong* with membership grade $\mu_S(y_{PR})$=1;
Input 2: STATUS is *medium* with membership grade $\mu_M(y_{ST})$=0.60 and *strong* with membership grade $\mu_S(y_{ST})$=0.70;
Input 3: RESPONSE is *medium* with membership grade $\mu_M(y_{RE})$=1 and *weak* with membership grade $\mu_W(y_{RE})$=0.45.

We now compute the degree to which each rule is applicable to the input. Using the min-operator to represent the AND connectives of rule *r*, *r*=1, . . ., 27, Eq. (4) reduces to

$$\mu_{\mathrm{PREMISE}_r} = \min\{\mu_i(y_{\mathrm{PR}}), \mu_j(y_{\mathrm{ST}}), \mu_k(y_{\mathrm{RE}})\}$$

where μ_{PREMISE_r} is the degree to which rule, *r*, is applicable and *i*, *j*, *k*∈{W, M, S}. The only consistent rules are those in which PRESSURE is *strong*, STATUS is either *strong* or *medium*, and RESPONSE is either *weak* or *medium*. These are rules 22, 23, 25, and 26 of Table 5. The conclusions of these rules are expressed as follows:

Rule 22: If PRESSURE is *strong* with membership grade 1 and STATUS is *strong* with membership grade 0.70 and RESPONSE is *medium* with membership grade 1, then KNOW

Table 5
Third-order rule base for the computation of KNOW

Rule *r*	If PRESSURE is	And STATUS is	And RESPONSE is	Then KNOW is
1	weak	strong	strong	very good
2	weak	medium	strong	very good
3	weak	weak	strong	good
4	**weak**	strong	medium	very good
5	**weak**	medium	medium	good
6	weak	weak	medium	average
7	**weak**	strong	weak	good
8	**weak**	medium	weak	average
9	weak	weak	weak	bad
10	medium	strong	strong	very good
11	medium	medium	strong	good
12	medium	weak	strong	average
13	medium	strong	medium	good
14	medium	medium	medium	average
15	medium	weak	medium	bad
16	medium	strong	weak	average
17	medium	medium	weak	bad
18	medium	weak	weak	very bad
19	strong	strong	strong	good
20	strong	medium	strong	average
21	strong	weak	strong	bad
22	strong	**strong**	**medium**	**average**
23	strong	**medium**	**medium**	**bad**
24	strong	weak	medium	very bad
25	strong	**strong**	**weak**	**bad**
26	strong	**medium**	**weak**	**very bad**
27	strong	weak	weak	very bad

is *average* with membership grade $\mu_{\mathrm{PREMISE}_{22}}$= 0.70 (=min{1, 0.70, 1}).

Rule 23: If PRESSURE is *strong* with membership grade 1 and STATUS is *medium* with membership grade 0.60 and RESPONSE is *medium* with membership grade 1, then KNOW is *bad* with membership grade $\mu_{\mathrm{PREMISE}_{23}}$=0.60 (=min{1, 0.60, 1}).

Rule 25: If PRESSURE is *strong* with membership grade 1 and STATUS is *strong* with membership grade 0.70 and RESPONSE is *weak* with membership grade 0.45, then KNOW is *bad* with membership grade $\mu_{\mathrm{PREMISE}_{25}}$=0.45 (=min{1, 0.70, 0.45}).

Rule 26: If PRESSURE is *strong* with membership grade 1 and STATUS is *medium* with membership grade 0.60 and RESPONSE is *weak* with membership grade 0.45, then KNOW is *very bad* with membership grade $\mu_{\mathrm{PREMISE}_{26}}$= 0.45 (=min{1, 0.60, 0.45}).

For the remaining rules of the rule base, we have μ_{PREMISE_r}=0. We observe that rules 23 and 25 assign the same linguistic value *bad* to KNOW. Applying Eq. (5), we combine the conclusions of these rules into a single conclusion whose truth-value is given by

$$f_{\mathrm{KNOW,B}} = \max\{\mu_{\mathrm{PREMISE}_{23}}, \mu_{\mathrm{PREMISE}_{25}}\} = 0.60$$

where B stands for *bad*. From the other two rules, we obtain

$$f_{\mathrm{KNOW,A}} = \mu_{\mathrm{PREMISE}_{22}} = 0.70,$$
$$f_{\mathrm{KNOW,VB}} = \mu_{\mathrm{PREMISE}_{26}} = 0.45$$

where A and VB signify *intermediate* and *very bad*, respectively. The above membership grades constitute the output of the inference engine. The inference process for KNOW is illustrated in Fig. 8. This figure shows also the membership functions of the linguistic values assigned to KNOW. Because the membership functions of *bad* and *average* are symmetric about the normalized indicator values 0.3 and 0.5, respectively, the peak values used in height defuzzification are invariant and equal to these values. The peak value of the fuzzy subset of *very bad* corresponding to $f_{\mathrm{KNOW,VB}}$=0.45 is obtained from Eq. (7): $p_{\mathrm{KNOW,VB}}$=(0+0.21)/2=0.105. Applying Eq. (8) for defuzzification, we obtain a crisp value for KNOW

$$y_{\mathrm{KNOW}} = \frac{0.45 \times 0.105 + 0.60 \times 0.3 + 0.70 \times 0.5}{0.45 + 0.60 + 0.70} = \frac{0.57725}{1.75} = 0.329857.$$

We now calculate the gradients of y_{KNOW} with respect to the inputs, y_c, $c \in$ {PR, ST, RE}. For simplicity in the calculations, we introduce a fixed perturbation, δ_c=0.001, for each input indicator c. For this perturbation, the membership functions of *weak*, *medium*, and *strong* (see Fig. 7) are linear in the intervals [y_c−0.001, y_c+0.001]. Therefore, the left and right derivatives at y_c are equal to the derivative at this point and can be computed using any difference quotient (central, forward, or backward). Similarly, the output, y_{KNOW}, obtained after inference and defuzzification is differentiable at (y_{PR}, y_{ST}, y_{RE}). However, because y_{KNOW} is nonlinear, the difference quotients with respect to any input variable will produce different estimates of the partial derivative of this function to the same input variable. Although central-difference quotients are expected to be better approximations than the others, here we use forward-difference quotients because they require fewer computations. The forward-difference quotient with respect to y_c is defined as

$$\Delta^{(c)}_{\mathrm{KNOW}} = \frac{y_{\mathrm{KNOW}}(y_c + \delta_c) - y_{\mathrm{KNOW}}}{\delta_c}$$

where $y_{\mathrm{KNOW}}(y_c+\delta_c)$ denotes the crisp value of KNOW when y_c is increased by δ_c, all other inputs being unchanged.

Increasing y_{PR} from 0.90 to 0.901 has no effect on y_{KNOW} because $\mu_{\mathrm{S}}(0.90)=\mu_{\mathrm{S}}(0.901)=1$. Thus,

$$\Delta^{(\mathrm{PR})}_{\mathrm{KNOW}} = 0$$

Similarly, increasing y_{RE} from 0.41 to 0.411 does not affect $\mu_{\mathrm{M}}(y_{\mathrm{RE}})$. However, $\mu_{\mathrm{W}}(y_{\mathrm{RE}})$ is decreased from 0.45 to 0.445. Thus $f_{\mathrm{KNOW,VB}}=\mu_{\mathrm{PREMISE}_{26}}$=0.445, and the peak of the fuzzy subset of very low is

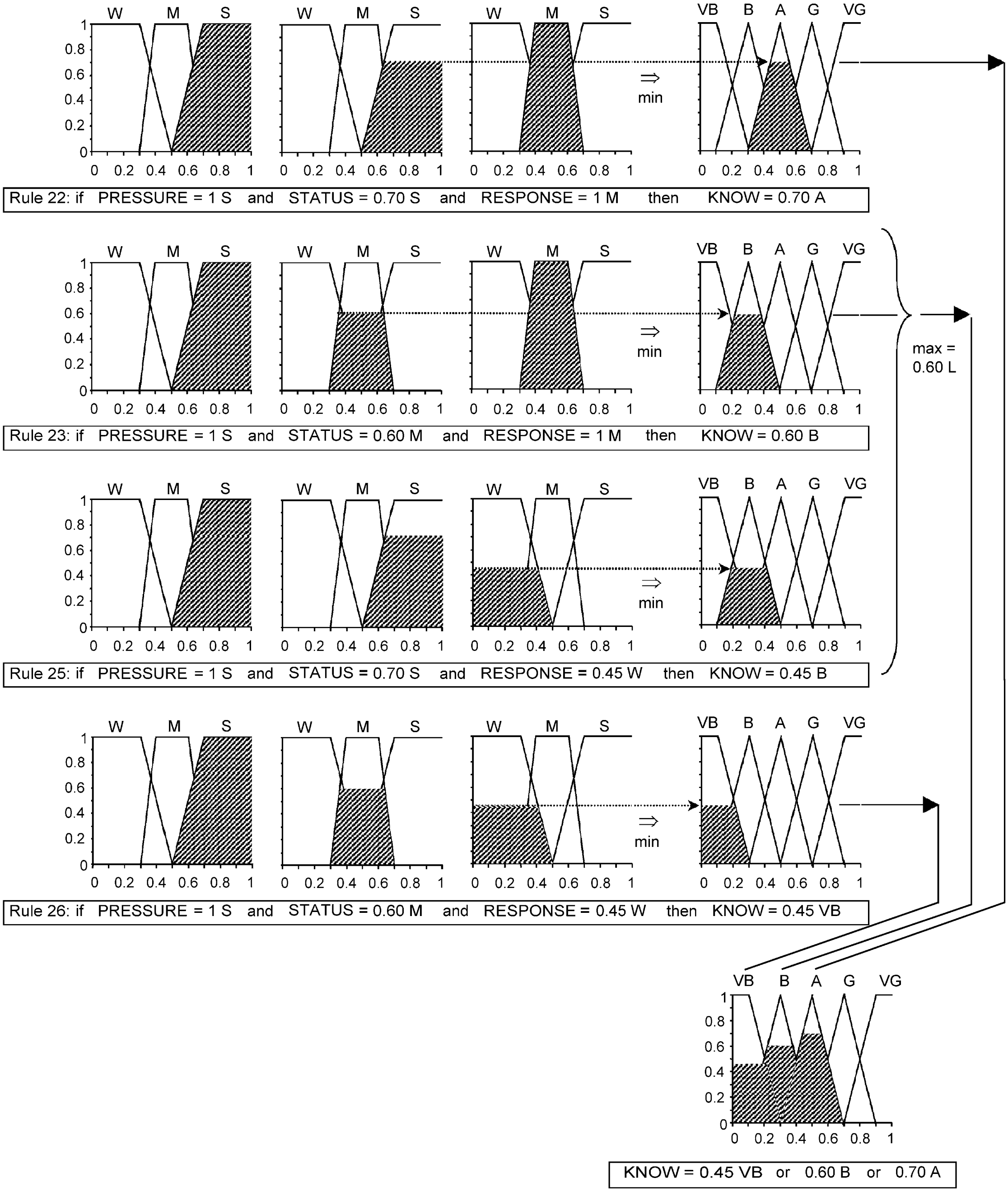

Fig. 8. Inference using rules 22, 23, 25, and 26.

$p_{\mathrm{KNOW,VB}}$=(0+0.211)/2=0.1055. All other parameters being unchanged, applying the height formula of defuzzification yields $y_{\mathrm{KNOW}}(y_{\mathrm{RE}}$+0.001)=0.57695/1.745=0.330630, and an approximate value of the partial derivative of y_{KNOW} with respect to RESPONSE is

$$\Delta_{\mathrm{KNOW}}^{(\mathrm{RE})} = 0.773.$$

Finally, increasing y_{ST} from 0.64 to 0.641 results in a decrease of $\mu_M(y_{ST})$ from the value 0.60 to 0.59 and an increase of $\mu_S(y_{ST})$ from the value 0.70 to 0.705. In this case, we obtain $y_{KNOW}(y_{ST}+0.001)=0.57675/1.745=0.330516$ and

$$\Delta_{KNOW}^{(ST)} = 0.659$$

The same procedure is used to determine y_{LAND}, y_{WATER}, y_{AIR}, y_{POLIC}, y_{HEALTH}, y_{WEALTH}, y_{KNOW} and their gradients (if needed), as well as the primary components y_{ECOS}, y_{HUMS}, and the overall sustainability y_{OSUS}.

As noted before, the height formula of defuzzification is nonlinear in the values of input indicators. Therefore, the difference quotients, Δ, are approximations of the partial derivatives of y_s. Yet, an exact sensitivity analysis is still possible. By taking derivatives with respect to the normalized values, y_c, on both sides of Eq. (8), after a little algebra, we obtain

$$\frac{\partial y_s}{\partial y_c} = \frac{\sum_v \frac{\partial p_{s,v}}{\partial y_c} f_{s,v} + \sum_v \frac{\partial f_{s,v}}{\partial y_c} p_{s,v} - y_s \sum_v \frac{\partial f_{s,v}}{\partial y_c}}{\sum_v f_{s,v}}$$

The functions, $p_{s,v}$ and $f_{s,v}$, are piecewise linear in y_c for every input indicator c. Therefore, the derivatives of these functions could be estimated exactly using difference quotients and the gradient of y_s using the above equation.

It should be noted that the above equation corresponds to a single-rule base of the SAFE model. The gradients of the overall sustainability to the basic indicators (the nonnormalized inputs to the whole system) could be computed by applying this equation for each knowledge base to obtain the gradients of its output to its inputs and, finally, by applying the chain rule of differentiation. An exact sensitivity analysis might be useful in solving optimization problems. Currently, the SAFE system uses difference quotients to approximate the partial derivatives of overall sustainability. From a number of numerical experiments, it appears that this approximation provides very good sensitivity estimates. For instance, the partial derivatives of y_{KNOW} in the previous example are

$$\frac{\partial y_{KNOW}}{\partial y_{PR}} = 0, \; \frac{\partial y_{KNOW}}{\partial y_{RE}} = 0.770, \; \frac{\partial y_{KNOW}}{\partial y_{ST}} = 0.657$$

The estimates of the SAFE model are off these values by less than 0.4%. Therefore, difference quotients are very good approximations. Furthermore, because the composite indicators are not everywhere differentiable, the use of difference quotients (subgradients) and special optimization algorithms can cope with nondifferentiability in optimization problems.

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