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Solution spaces for decision-making—a sustainability assessment tool for city-regions

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Abstract

The sound development of city-regions presents a major planning challenge, as these regions are and will be the living spaces for the majority of the population. Therefore, a key question is how city-regions can be managed so that they develop in a sustainable way. Although Environmental Impact Assessment, Integrated Assessment, and other currently used approaches provide significant inputs for managing transition-processes towards sustainability, they must be extended to respond to three major deficiencies, which are (i) using lists of isolated indicators, (ii) not performing a consistency analysis of the targets to be achieved, and (iii) not utilizing the potential of transdisciplinary approaches. The authors present an approach to constructing Sustainability Solution Spaces for Decision-Making (SSP). This approach fulfils the systemic, normative, and procedural requirements of an appropriate sustainability assessment as elaborated in the technical literature. It provides a consistent set of targets considering the systemic relations among the indicators representing the city-region. This gives the decision-makers a concise guideline for sustainable decisions and makes them aware of the synergistic and contradictory effects of their decisions. The modular tool is first depicted as a general procedure and later differentiated into two transdisciplinary approaches, a participatory and an expert approach.

Keywords: Sustainability assessment; Sustainability indicators; City-regions; Decision support tool; Target conflicts; Transdisciplinarity

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1. Introduction

The sound development of city-regions is one of the important environmental, economic, social, and cultural challenges of the future, as cities are and will be the domiciles, working places, and social activity spaces for the majority of the population (cf. Ravetz, 2000b; Ache, 2000; Rees and Wackernagel, 1996). One key question is how city-regions (urban–rural agglomerations) should be managed in order to avoid economic decline, social instability, and environmental depletion (cf. Rotmans et al., 2000; Devuyst et al., 2001). According to Nijkamp and Vreeker (2000, pp. 9ff.), a multidimensional sustainability assessment tool is needed to address this issue. The tool should include (i) a normative guiding concept operationalised in specific targets (normative dimension), (ii) a target-related model of the system to be assessed (systemic dimension), and (iii) an appropriate procedure to integrate the relevant stakeholders and to bridge normative and systemic aspects (procedural dimension) (Fig. 1).

Concerning the normative dimension, the main challenge is how the widely accepted concept of sustainable development can be applied to city-regions (cf. Finco and Nijkamp, 2001). That is, there is a need to derive precise targets from the general concept of sustainability that match the specific problems of the city-region (problem and goal orientation). In addition, these targets need to be internally consistent and at the same time allow decision-makers flexibility for taking measures.

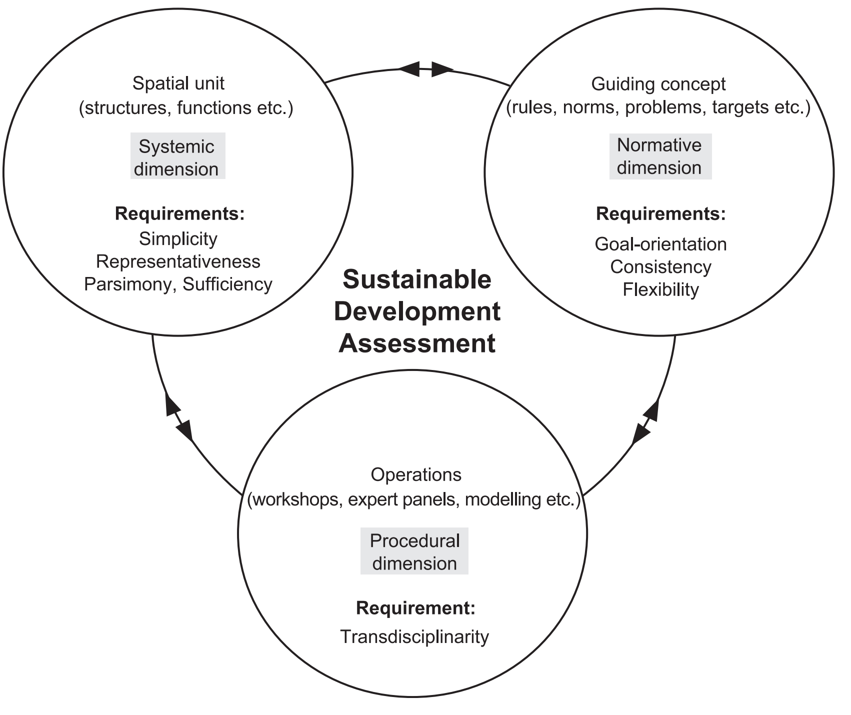

Fig. 1. Requirements for assessing the sustainability of city-regions by including normative, systemic, and procedural aspects.

Several efforts have been made to tackle the issues within the systemic dimension. There is broad consensus that designing complex system models, which depict the city-region in every detail, is too time- and money-consuming. Therefore, indicators which simplify system representation are used to describe and monitor the system to be assessed (cf. United Nations, 1993, p. 284). It is agreed that indicators should represent the main structures, processes, and functions of the economic, ecological, and social fields of the city-region referring to the problems and targets determined in the normative dimension (problem and target-oriented representativeness). An issue that still has to be tackled, however, is how to include the relations among the indicators in the analysis, as city-regions are complex interactive networks characterized by various structural and dynamic linkages. Thus, the system should be represented with as much simplicity as possible (parsimony) and as much complexity as necessary (sufficiency).

Finally, with respect to the procedural dimension, it has been shown that the assessment is more likely to yield good results if it is designed as a transdisciplinary approach (cf. Ravetz, 1999; Thompson Klein et al., 2001). This allows for involving stakeholders with different viewpoints, obligations, skills, and resources in the transition process of a city-region. The transdisciplinary approach provides a framework with which to adapt the assessment tool to the perceptive, cognitive, and discursive skills of the stakeholders as well as to their preferences and values in order to support socially stable and scientifically founded decisions.

Within the last decade, various indicator-based sustainability assessment approaches for city-regions have been developed and applied, e.g., Environmental Impact Assessment, Integrated Assessment, Pressure-State-Response frameworks, approaches using input–output sets of indicators (Regional Material Flux Analysis) or focussing on land use (Ecological Footprint, Sustainable Process Index), and Carrying Capacity Concepts (cf. compendiums by Moldan et al., 1997; Hardi and Zdan, 1997; Petts, 1999; Bossel, 1999; Rotmans and van Asselt, 2002; Linser, 2002; Robert et al., 2002; Bell and Morse, 2003; Carey, 1993). Without a doubt, these approaches provide important information for and are the basis of integrative sustainability assessment tools such as Ravetz (2000a), Rotmans et al. (2000) and Devuyst et al. (2001).

However, these approaches show deficits with respect to the requirements compiled above (cf. Bossel, 1999; Morse et al., 2001; Linser, 2002). Regarding the normative dimension, current approaches mostly focus on optimizing the system analysis, neglecting to define specific targets related to principles of sustainable development that can be derived from system theory approaches (cf. Bossel, 1999; Robert, 2002). Even if specific targets are defined, they are often inconsistent and, moreover, so narrowly defined that the necessary flexibility for decision-making is not given. Concerning the systemic dimension, the most often used “indicator lists” are deficient with respect to the accurate (parsimonious and sufficient) representation of the system and its problems. They consider neither all dimensions of sustainability nor the interlinkages among the indicators nor the interdependency with other systems (cf. Scholz and Tietje, 2002, pp. 308f.; Vester, 1988). Finally, regarding the procedural dimension, the current approaches often do not sufficiently apply transdisciplinary methods. Given these deficits, Deelstraa et al. (2003), Fischer (2003), Mulvihill (2003) and Rotmans and van Asselt (2002) claim that an extension of Environmental Impact Assessment, Integrated Assessment, etc. to a comprehensive sustainability assessment framework is needed.

In this paper we introduce a tool to construct a Sustainability Solution Space for Decision-making (SSP). This decision support tool fulfils the requirements of an appropriate sustainability assessment by integrating systemic and normative knowledge of the relevant stakeholders and therefore contributes to the necessary extension of environmental assessment tools. It provides a consistent set of targets considering the systemic relations among the indicators representing the city-region.

In this paper, we present the concept underlying the SSP tool on a theoretical level and illustrate the main elements of the tool.

2. Constructing a Sustainability Solution Space for Decision-making (SSP)

The construction of an SSP considers systemic knowledge (Module I) and normative aspects (Module II) aiming at their integration (Module III). It is divided into six steps (Fig. 2). Preliminary to starting the construction of an SSP, the goal (i.e., to achieve sustainable development of the city-region), involved stakeholders, and the specific procedure are defined considering the interests and problem perception of the user group (decision-makers). Based on this, in Module I a system analysis is carried out, including system characterization, indicator selection, and analysis of the linkages among the indicators. In Module II, targets for each indicator are set in form of target ranges. Finally, in Module III, the target ranges are linked to the system analysis in order to identify target conflicts and to establish the SSP. The

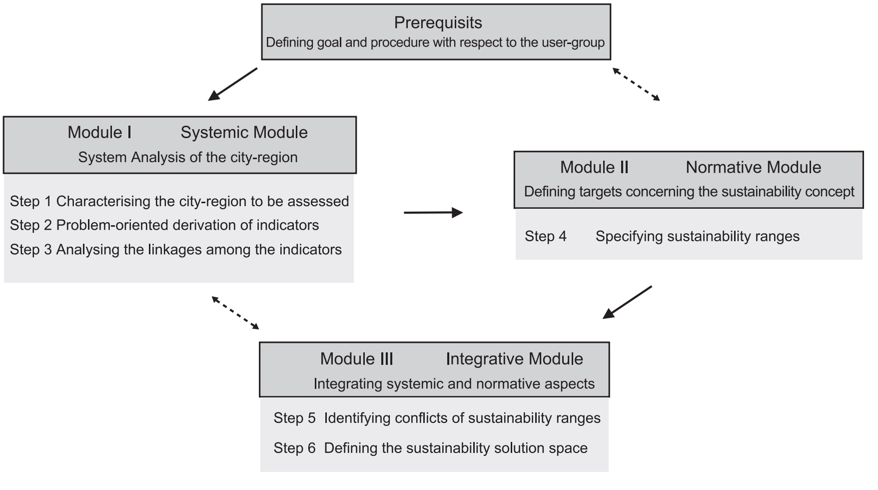

Fig. 2. The modules and steps of constructing an SSP.

procedure, although it is depicted as a linear one, is iterative, switching between normative and systemic aspects.

2.1. Prerequisites

As with any assessment, it is indispensable that the user group, e.g., planners or policy makers, defines goal, function, and involved stakeholders prior to carrying out the construction of an SSP. For example, a task force composed of members from government and administration (users) wants to apply the tool, aiming at a sustainable development of a city-region (goal). Using this tool as a monitoring, evaluating, or steering instrument (function), the task force involves entrepreneurs, consumers, NGOs, and experts (stakeholders) on an informative and consultative participation level (Oxley Green and Hunton-Clarke, 2003, pp. 295f.). Depending on the involved stakeholders, we distinguish two procedures: the participatory and the expert approach (Table 1).

The participatory approach enables "affected persons", e.g., citizens or entrepreneurs, to articulate and discuss their perspectives on the city-region and its development. The methods included in this approach are derived from Group Techniques Theory, Integrated Assessment, etc. and are adapted to the perceptive, cognitive and discursive skills of "laypersons" (cf. Rotmans, 1998, pp. 162f.). Thus, they make extensive use of visualising, simple structuring, and connecting techniques (cf. Kasemir et al., 2003; Scholz and Tietje, 2002; Tietje, in preparation).

The expert approach is appropriate if the problem is too complex to be tackled with laypersons or requires a deeper professional insight (cf. Mieg, 2001). In this case, the stakeholders are experts, e.g., academics, researchers, jurists, who are trained in the required fields. Involving experts ensures transparency of the assessment with respect to the "state of the art" in the related scientific fields. The methods included are derived from system theory and operations research and rely on computer-based information systems (cf. Jackson, 1998).

Table 1
Comparison between the participatory and the expert approach with respect to user group, goal, function, involved stakeholders, knowledge, and methods

	Participatory approach	Expert approach
Users (lead)	Policy makers and planners	
Goal	Sustainability optimization of a city-region or a sector	
Functions	Monitoring, evaluating, steering	
Participation level	Informative, consultative	
Involved Stakeholders	"Affected" persons e.g., citizens, officials, entrepreneurs	Experts, e.g., academics, researchers (institutes, NGOs), jurists
Systemic Knowledge	Experiences	Expertise
Normative Knowledge	Preferences	Principles
Methods (adapted to the skills of the involved persons)	Facilitating, visualising, simple structuring, and connecting techniques	Scientific and computer-based information systems, analytical tools, and evaluation methods

2.2. Module I. System analysis of the city-region by using an integrated set of indicators (Systemic Module)

The goal of the systemic module (steps 1–3) is to obtain a sufficient (descriptive) model of the city-region, including specifications about boundaries, indicators, their inter- and intrarelations, and dynamics. This concept is compatible with the Structure–Function–Context model of the Bio-Ecological Potential Analysis (Scholz and Tietje, 2002, pp. 306ff.), linking structure (boundaries, indicators), functions (intrarelations, dynamics), and context (interlinkages) of a system in a comprehensive assessment approach.

Step 1. Characterising the city-region to be assessed

The first step of the system analysis is to determine the geographic, biophysical, and socioeconomic characteristics of the city-region (cf. Musters et al., 1998). This leads to a common understanding of the city-region. In addition, problems related to the goals of the user group maybe identified and discussed, giving insight into the diversity of perspectives of the involved stakeholders (cf. Kasemir et al., 1999).

Step 2. Problem-oriented derivation of indicators

The indicators are selected based on the system characterisation of the city-region (step 1) and the goals defined by the user group (prerequisite). They have to fulfil the following criteria:

- They must represent the main economic, ecological, and social aspects of the city-region with respect to its specific problems related to sustainable development issues (cf. Rotmans and van Asselt, 2002; Malkina-Pykh, 2000, p. 70).
- They must be measurable and easy to communicate (Linser, 2002, pp. 14ff.).

The cooperating researchers revise the preselected indicators criteria-based, following principle-oriented concepts of sustainable development (cf. Bossel, 1999; Robert, 2002). This finally leads to the definite set of indicators fulfilling the requirement of transdisciplinarity.

Step 3. Analysing the inter- and intralinkages among the indicators as well as their dynamics

To determine the inter- and intralinkages among the derived indicators, a simplified systemic model of the city-region is needed (cf. Malkina-Pykh, 2000), which should include:

- Intralinkages among the indicators (cf. Moldan et al., 1997; Becker et al., 1997, pp. 23f.; Rothman et al., 2002, pp. 182ff.). This means analyzing the interdependencies among the indicators from environmental, economic, social, and other thematic fields (cf. OECD, 2000, p. 13).
- Interlinkages between the indicators of the city-region and the contextual systems, i.e., the “hinterland” (Bossel, 1999, pp. 10f.; Scholz and Tietje, 2002, pp. 308f.). These can be determined either by the polluter-pay-principle or by the concept of “functional

differentiation/disaggregation of space" (cf. Thierstein and Walser, 2000, pp. 76f.), which classifies areas with respect to their different functions of production (with pollution), compensation, regeneration, etc.
- Dynamics of the indicators at the micro- and macrolevel (cf. Linser, 2002, p. 35).

2.3. Module II. Defining targets concerning the concept of sustainable development (Normative Module)

This module aims at incorporating scientific judgements, values, and preferences related to the results of the system analysis (Module I).

Step 4. Specifying the sustainability ranges for the indicators

To progress from an inventory to an assessment of the city-region, specific targets for each of the derived indicators have to be defined (cf. Ravetz, 2000b, pp. 10, 32f.).

The target setting process is based on principles of sustainable development and neither on the reference to a former state of the city-region (progress or trend) nor on the reference to the state of a different city-region (benchmarking). Clayton and Radcliffe (1996), Bossel (1999), and Robert (2002), among others, define general criteria, system conditions, and principles of sustainable development. These criteria are applied to the development of a specific city-region to define indicator-related targets. This is not a technical procedure but an adaptive "translation" which considers particularities of the city-region.

In many cases, the persons in charge face difficulties in determining a discrete target value for a specific indicator. This is due to scientific uncertainties, socioeconomic imponderability as well as political constraints.

For this reason, we advocate defining "sustainability ranges" (minimum and maximum threshold values) for the indicators (cf. the concept of constraints in Bossel, 1999, pp. 4ff.). This is done in contrast to the common practice of determining one discrete threshold value for each indicator. The sustainability range of an indicator is the largest range within which a sustainable development can take place. Defining a range instead of one threshold value allows for a greater flexibility in decision-making (optimal allocation).

2.4. Module III. Integrating systemic and normative aspects (Integrative Module)

This module integrates the systemic and the normative aspects elaborated in Module I and II, respectively.

Step 5. Identifying conflicts among the sustainability ranges

The complex interrelations among economic, environmental and social judgements, values, and preferences of the stakeholders lead in almost every case to conflicts among the targets, which are usually set from a sector specific perspective (cf. Campbell, 1996). The examination of the consistency among the defined sustainability ranges reveals these conflicts and is a prerequisite for successful negotiations among different interest groups.

Step 6. Defining the sustainability solution space for decision-making

In the final step, the conflicting ranges identified in step 5 are harmonized to constitute the SSP. There are three approaches to doing this:

- Prioritizing the targets. Ranking the indicator-related targets according to their relevance for the goals set by the user group (decision-makers).
- Optimizing the target composition. Adjusting all conflicting ranges to obtain the largest possible solution space. This approach goes beyond the differentiation of compensatory and antagonistic approaches (Scholz and Tietje, 2002, pp. 170f.). By defining the SSP by two threshold values for each indicator, both of these aspects are integrated. One of the two boundaries of the indicator is fixed as a minimum quality standard, and the upper boundary is adapted with respect to the fixed boundaries of the other indicators.
- Adapting the system. Defining targets not only for the indicators but also for their systemic relations. That is, defining a potential system change in the future, e.g., implementing an energy efficient technology, which is likely to change the relation between kilometres driven with a car and fuel consumption.

The result of this step is an SSP comprising a consistent set of sustainability ranges related to indicators which represent the city-region.

3. The participatory approach

If a participatory approach is the suitable tool for the specified stakeholder group (cf. 2.1. Prerequisites), a workshop design is suggested as the appropriate procedure (cf. Sanoff, 2000).

3.1. Indicator derivation and system analysis

To identify the relevant indicators of the city-region development, unstructured procedures are used, such as brainstorming methods visually supported by mind mapping methods. The participants gather variables, which they consider relevant for the state and development of the city-region, and group them according to the subsystems of the city-region, e.g., in demographic, environmental, economic, social, institutional, and other aspects (Table 2).

Table 2
Example of an indicator list categorizing relevant aspects of the city-region development (the indicators used in the following examples are highlighted)

Environmental Aspects	Economic Aspects	Social Aspects
Air Pollution	Income Average	Quality of Housing (e.g. Noise)
Waste	Taxes	Public Transportation Facilities
Erosion	Unemployment Rate	Safety

The cooperating researchers revise the list of indicators preselected by the participants following principle-oriented concepts of sustainable development (cf. Bossel, 1999; Robert, 2002). This finally leads to the definite set of indicators.

To analyze the systemic relations among the selected indicators, an impact analysis is performed according to Formative Scenario Analysis by Scholz and Tietje (2002, pp. 79–116) or the biocybernetic approach of Vester (1988). The participants define for each pair of indicators the strength of the one-directional impact between them (0 as no, 1 as weak, 2 as strong direct relationship). For example, the indicator “taxes” has a high impact on the indicator “public transportation facilities”, which itself has a high impact on the indicator “air quality”. An external person facilitates the impact appraisal process and fixes the results in an impact matrix (Table 3). Additionally, the participants may determine the type of impact (cooperative, conflicting, or indifferent).

This matrix can be evaluated using the software MicMacD (Tietje, in preparation), leading to a system graph and a system grid. The system graph visualises the relations among the indicators (Fig. 3A). The system grid represents the numerically aggregated impact strengths for each indicator and classifies the indicators depending on their type of “system impact” as active, passive, ambivalent, or indifferent (Fig. 3B).

The benefit of visualising the system analysis results by means of graphs and grids is that the isolated and dispersed details of the systemic knowledge are compiled. The position and interactions of each indicator within the system become available for a

Table 3
General influence matrix showing the strengths of the impacts among the indicators (0 as no, 1 as weak, 2 as strong direct relation)

	→	Environmental Aspects			Economic Aspects			Social Aspects		
		Indicator env 1	Indicator env 2	Indicator env 3	Indicator econ 1	Indicator econ 2	Indicator econ 3	Indicator soc 1	Indicator soc 2	Indicator soc 3
Environmental Aspects	Indicator env 1		0	1	0	1	0	2	1	0
	Indicator env 2	0		1	0	1	0	2	1	0
	Indicator env 3	1	1		0	1	0	1	1	0
Economic Aspects	Indicator econ 1	1	1	1		1	0	1	1	1
	Indicator econ 2	1	1	1	2		0	1	1	0
	Indicator econ 3	1	1	1	2	0		1	0	0
Social Aspects	Indicator soc 1	1	1	2	0	0	0		1	0
	Indicator soc 2	2	2	2	1	0	0	2		1
	Indicator soc 3	1	1	1	1	1	0	2	1	

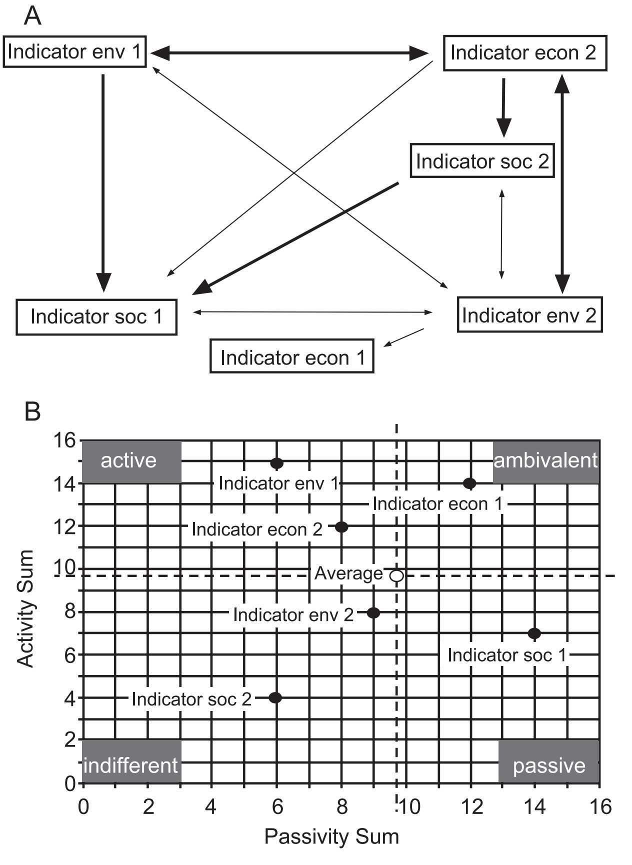

Fig. 3. General system graph (A) and general system grid (B) depicting the influence structure among the environmental, economic, and social indicators (thin arrows as weak, thick arrows as strong direct influence) and the type and degree of the "system influence" of each indicator, respectively.

systemic review "in a single perception". On this basis, key variables as well as overrated variables of the system can be identified. The benefit of such an information aggregating and integrating technique is further enhanced by attaching qualitative data to the visualised influences (e.g., supporting, repressing, level of steering, etc.).

3.2. Range setting and consistency analysis

To determine the sustainability ranges for each indicator, the participants single out and discuss a minimum and maximum threshold value for each indicator. These values should consider (i) the goal of applying the assessment tool set by the user group (decision-makers), (ii) legal threshold values (e.g., air pollution thresholds), or (iii) other reference values. The sustainability range is the largest range within which a sustainable development of an indicator is possible. The range of each indicator, however, is constrained by its relationship to and the thresholds of the other indicators. For example, a high level of public transportation facilities might not be compatible with a minimum tax level but might be consistent with low air pollution.

To determine the compatibility among the indicator ranges, a consistency analysis (cf. Scholz and Tietje, 2002; Tietje, in press) is performed in which the participants evaluate the relation among the indicator threshold values by pairs (e.g., minimal threshold of indicator 1 with maximum threshold of indicator 2) as, for instance, cooperative, conflicting, or indifferent. The results of the consensus process are fixed in a matrix (Table 4). This matrix reveals the indicator threshold values that are in conflict with the other indicators and thus makes target conflicts apparent.

The participatory approach is based on a bivariate procedure. Multivariate relationships cannot be directly handled within this approach. However, the consistency matrix analyzes how the target values of each indicator relate to each of the target values of the other indicators.

To solve the target conflicts identified, there are three different ways mentioned above (2.4., step 6). (i) Prioritizing the targets. For example, reducing taxes could be regarded by the participants as more important than the target of having a high level of public services and a low level of air pollution. Thus, the thresholds of the latter two indicators have to be changed to be compatible with the narrow range of the indicator “taxes”. (ii) Optimizing the threshold ranges. To do this, the participants select two intermediate values between the maximum and the minimum threshold values of the indicator ranges that were in conflict with each other. On this basis, they perform an additional consistency analysis for these indicators (iterative procedure). (iii) Adapting the system. This approach goes beyond the relations identified by suggesting, for instance, new mechanisms for achieving a high level of air quality (polluter-pay-mechanisms, emission certificate trading, etc.). This implies a change of systemic interdependencies between taxes, public transportation, and air quality, and seizes the opportunity to reach the set targets via alternative solutions.

Solving the conflicts among the ranges requires a consensual process in the group leading to concrete solutions. The result is, finally—besides the raised awareness about normative–systemic interactions—an SSP (Fig. 4).

Table 4
General consistency matrix showing for each indicator a maximum and a minimum target value as well as the type of relation among the indicator targets (−1 as conflicting, 0 as indifferent, 1 as cooperative)

		Indicator env 1		Indicator econ 1		Indicator soc 1	
	↔	Max. Target	Min. Target	Max. Target	Min. Target	Max. Target	Min. Target
Indicator	Max. Target	X	X	X	X	X	X
env 1	Min. Target	X	X	X	X	X	X
Indicator	Max. Target	-1	0	X	X	X	X
econ 1	Min. Target	0	-1	X	X	X	X
Indicator	Max. Target	0	1	0	0	X	X
soc 1	Min. Target	1	0	0	-1	X	X

Conflicting relationships are highlighted.

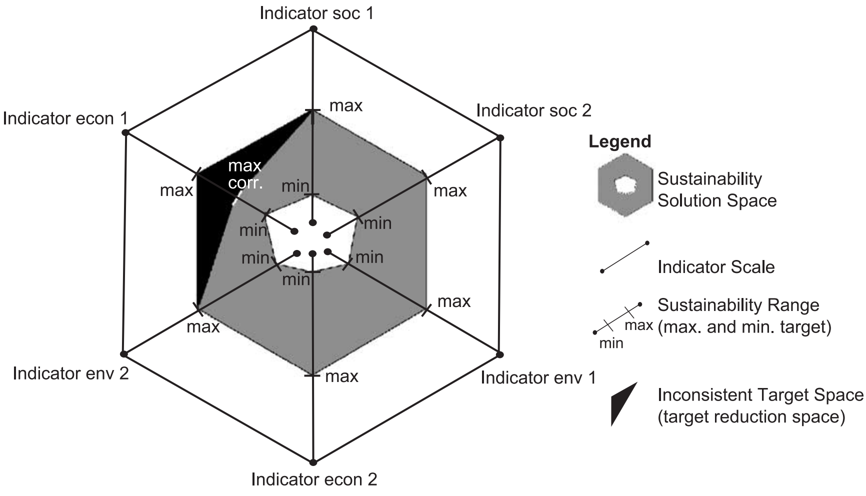

Fig. 4. Projection of a general SSP. The spider-gram represents the systemic interactions among the indicators. On this basis, a consistent set of targets is achieved, which constitutes the SSP.

The SSP can be depicted as a graph consisting of indicator scales and sustainability ranges for each indicator (maximum and minimum target) as a frame. The solution space obtained is n-dimensional (n=number of indicators). Within it, the corrected threshold values define the SSP and a complementary target reduction space composed of the inconsistent target spaces.

4. The expert approach

If an expert approach is the appropriate tool for the specified stakeholder group (cf. 2.1. Prerequisites), methods from expert judgement design (Mieg, 2001), system dynamics (Vennix, 1996) and operations research (Taha, 1989) could be applied.

4.1. Indicator derivation and system analysis

To identify the relevant indicators, we use structured procedures such as the Repertory Grid Method or other knowledge elicitation techniques (cf. Bringmann, 1992; Mieg, 2001). The cooperating researchers revise the list of indicators preselected by the experts following principle-oriented concepts of sustainable development (cf. Bossel, 1999; Robert, 2002). This finally leads to the definite set of indicators.

The indicators are precisely defined, and an appropriate set of empirical data including indicator dynamics is needed.

The selected indicators are analyzed by modelling their interactions as mathematical multivariate equations, as it is performed, for instance, in material flux analysis and social–economic decision models. This leads to a complex mathematical model of the city-region (cf. Vennix, 1996, pp. 69–100).

4.2. Range setting and sustainability ranges

Two different approaches can be selected for setting the targets and the sustainability ranges: (i) the numerical solution and (ii) the maximization/minimization procedure. Both approaches are based on optimization theory from operations research and lead to a consistent maximal solution space (cf. Taha, 1989).

4.2.1. Numerical solution

In the numerical solution approach, the experts determine, similarly to the participatory approach, two thresholds for each indicator (a maximum and a minimum). They base themselves on the principle-oriented approaches mentioned above and utilize the scientific expertise available (cf. Müller and Leupelt, 1996). For determining the sustainability ranges, the mathematical equations elaborated in the system analysis are utilized. Each indicator is expressed as a function of the other indicators related to it. Thus, for n indicators, a maximum of $n-1$ equations are needed to describe the system. As two threshold values were determined for each indicator, the system is overdefined, and thus, it is possible to identify inconsistencies between the selected ranges. In an iterative procedure, for each indicator, all possible threshold levels are determined numerically by using the threshold values of the other indicators as input values. If a solution (an adapted lower and upper threshold value) is obtained for all indicators, the sustainability solution space is determined. If no solution is found for all indicators, the same procedures as those described for the participatory approach can be applied. Below, the numerical approach is exemplified for the case of two indicators.

A sustainability range is represented as a set of valid target values. Considering the case of two indicators, x and y, the sustainability range of x, i.e., $X=[x_1, x_2]$, defines a preliminary solution space P_X in a two-dimensional space. Analogously, the preliminary solution space P_Y is defined as $Y=[y_1, y_2]$.

Given the relationship between x and y, the sustainability range of x induces a target range for y defined by Eq. (1).

$$f(x) = [f(x_1), f(x_2)] = Y' = [y_1', y_2'] \tag{1}$$

This target range is not necessarily identical with the sustainability range of y. Analogously, the new target range of x is defined by Eq. (2).

$$f^{-1}(y) = [f^{-1}(y_1), f^{-1}(y_2)] = X' = [x_1', x_2'] \tag{2}$$

The following relations between the two preliminary solution spaces, P_X and P_Y, can be observed:

(1) Intersection[2], $P_X \cap P_Y$
(2) Mutual exclusion, $\varnothing_{P_X, P_Y}$.

[2] This includes the special case that P_x is a subset of P_Y, i.e., $P_x \in P_Y$.

In the first case, the sustainability solution space (SSP) is defined as the intersecting area of P_x and P_Y (Eq. (3)). That is

$$f^{-1}(y)\in[x_1,x_2] \text{ and } f(x)\in[y_1,y_2] \tag{3}$$

In this case, the new sustainability ranges for x and y are defined in Eqs. (4) and (5), respectively:

$$\tilde{X} = [\tilde{x}_1,\tilde{x}_2] = \left[\max\left(x_1,f^{-1}(y_1)\right),\min\left(x_2,f^{-1}(y_2)\right)\right] \tag{4}$$

$$\tilde{Y} = [\tilde{y}_1,\tilde{y}_2] = [\max(y_1,f(x_1)),\min(y_2,f(x_2))] \tag{5}$$

The SSP is then defined by these new sustainability ranges as shown in Eq. (6):

$$P_{\tilde{X},\tilde{Y}} = ((x,y)|x\in[\tilde{x}_1,\tilde{x}_2],y\in[\tilde{y}_1,\tilde{y}_2] \tag{6}$$

In the second case, no intersection area can be defined. That is:

$$\begin{aligned}&(x|x\in[x_1,x_2] \cap x\in[f^{-1}(y_1),f^{-1}(y_2)]) = \emptyset \qquad \text{or}\\&(y|y\in[y_1,y_2]) \cap y\in[f(x_1),f(x_2)]) = \emptyset\end{aligned} \tag{7}$$

In this case, the sustainability ranges have to be adapted for obtaining a solution space for P_X and P_Y. This can be done following two guidelines: (i) changing the sustainability ranges of the indicators to achieve a congruent solution space and (ii) minimizing the changes of the sustainability ranges.

Below, we illustrate this procedure for two indicators. The relation between the two indicators, x and y, is defined as:

$$y = ax + c \Leftrightarrow x = \frac{1}{a}y - \frac{1}{a}c \tag{8}$$

The original sustainability ranges are defined as:

$$x\in[x_1,x_2] \qquad y\in[y_1,y_2] \tag{9}$$

The corresponding ranges, $[f^{-1}(y_1), f^{-1}(y_2)]$ and $[f(x_1), f(x_2)]$, are calculated by inserting the values of the sustainability ranges into Eq. (8).

$$\begin{matrix}f(x_1) = ax_1 + c\\ f(x_2) = ax_2 + c\end{matrix} \quad \text{and} \quad \begin{matrix}f^{-1}(y_1) = \frac{1}{a}y_1 - \frac{1}{a}c\\ f^{-1}(y_2) = \frac{1}{a}y_2 - \frac{1}{a}c\end{matrix} \quad \text{to} \quad \begin{matrix}f^{-1}(y)\in[f^{-1}(y_1),f^{-1}(y_2)]\\ f(x)\in[f(x_1),f(x_2)]\end{matrix} \tag{10}$$

The resulting ranges, $[\tilde{x_1},\tilde{x_2}]$ *and* $[\tilde{y_1},\tilde{y_2}]$ which define the SSP, are determined as follows:

(a) If the original sustainability range is smaller than the corresponding range, the original range is retained.

$$\begin{aligned}&[x_1,x_2] \subset [f^{-1}(y_1),f^{-1}(y_2)] \rightarrow \tilde{x_1} = x_1; \tilde{x_2} = x_2\\&[y_1,y_2] \subset [f(x_1),f(x_2)] \rightarrow \tilde{y_1} = y_1; \tilde{y_2} = y_2\end{aligned} \tag{11}$$

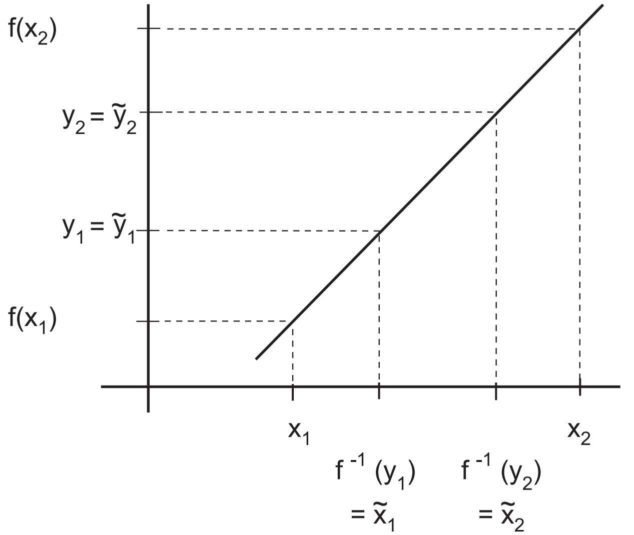

Fig. 5. A SSP is defined by the line depicting the function y=f(x) in the ranges $[\tilde{x}_1, \tilde{x}_2]$ *and*$[\tilde{y}_1, \tilde{y}_2]$. ([$x_1$, x_2] and [y_1, y_2]: original sustainability ranges; [$f^{-1}(y_1), f^{-1}(y_2)$] and [$f(x_1), f(x_2)$]: corresponding ranges (Eqs. (11) and (12))).

(b) If the original sustainability range is larger than the corresponding range, the latter range is selected.

$$\begin{aligned}&[x_1,x_2]\supset[f^{-1}(y_1),f^{-1}(y_2)]\rightarrow\tilde{x}_1=f^{-1}(y_1);\tilde{x}_2=f^{-1}(y_2)\\&[y_1,y_2]\supset[f(x_1),f(x_2)]\rightarrow\tilde{y}_1=f(x_1);\tilde{y}_2=f(x_2)\end{aligned}\tag{12}$$

The SSP is defined by the new sustainability ranges (in this case it is a line).

$$x\in[\tilde{x}_1,\tilde{x}_2]\qquad y\in[\tilde{y}_1,\tilde{y}_2]\tag{13}$$

The procedure is depicted in Fig. 5 exemplified for the case of a linear equation.

The graph (Fig. 5) shows on the x- and y-axes the original sustainability ranges (minimum and maximum target values) for the indicators x and y, respectively. Utilizing the mathematical relation between the indicators (function), the original solution space is reduced to the final SSP, which fulfils the conditions mentioned above.

4.2.2. Maximization/minimization procedure

In this procedure, the expert group determines only one threshold value (boundary threshold value), which should not be exceeded. For example, experts can rely on the law, stating the maximal air pollution values for a city-region. Again, the functions determined in the system analysis are used. For each nondefined threshold value of an indicator, an objective function (Eq. (14)) is defined. In addition, constraints given by the other indicators and their relationships are formulated (Eq. (15)). If for example the maximal tax rate was taken as the maximal threshold value, the taxes are minimized subject to the boundary threshold values of the other indicators affecting the tax rate. For example:

$$\text{Objective function}: \text{ minimize } y = f(x_1, x_2, \ldots x_{n-1}) \tag{14}$$

$$\text{Constraints}: \begin{aligned} x_1 + x_2 &= a \\ x_3 &< b \end{aligned} \tag{15}$$

where a and b are constants.

For linear relationships among the indicators, one optimal range can be identified for each indicator. An appropriate tool for doing this is linear programming (Taha, 1989). If the relationships are nonlinear, multiple solutions can be found, and therefore, different approaches have to be selected as described in operations research literature (Taha, 1989).

5. Discussion

Steering and decision-making for fostering sustainable development of city-regions is a multifaceted task (cf. Dörner, 1997). The goal of this paper was to contribute to this task by providing a transparent assessment procedure to support decision-making in complex city-regions. We developed a tool to define Sustainability Solution Spaces for Decision-making (SSP). It fulfils the requirements of an appropriate sustainability assessment, considering (i) normative aspects such as goal orientation, consistency, and flexibility; (ii) systemic aspects such as simplicity, representativeness, parsimony and sufficiency; and (iii) procedural aspects such as transdisciplinarity.

Concerning normative aspects, city-regions are often assessed by "reference" approaches based on comparison with former, potential, other city-regional or national states. These approaches promise sustainable development but often realise simple improvements only. In contrast to the reference approaches, within the normative module of the SSP, specific indicator-related targets are defined based on principles of sustainable development. They are established in the form of sustainability ranges with a maximum and a minimum limit allowing for flexibility (cf. Wilkins, 2003). In addition, the approaches presented enable social participation; that is, involved, affected, responsible, and interested stakeholders can participate in defining the goals and setting the sustainability ranges. Thus, this tool satisfies recommended standards of scientific sustainability research (Kasemir et al., 2003; Wilkins, 2003). One difficulty when applying this tool is how to assure the proper definition of the sustainability ranges. In the participatory approach, the facilitator faces the challenge that participants are usually not eager to reveal their values and preferences, even more so if these are beyond social acceptability (Brown, 2000). In the expert approach, the low availability of normative knowledge might inhibit an appropriate target setting (Becker et al., 1997). A second question involves the implications of potential divergences between experts' and lay persons' assessment. The transdisciplinary and consensual approach integrated in the SSP tool should ensure that a common vision involving minor divergences could be elaborated, which is open for further discussion and consensual processes.

Concerning the systemic module, two research trends can be identified. On the one hand, approaches such as material flux analysis, system dynamics, or geographic information system analysis aim at a comprehensive representation of the system. On the other hand, for assessment purposes, systemic complexity needs to be reduced to a workable representation due to limited cognitive capacities and resources for decision-making processes (Clayton and Radcliffe, 1996, p. 15; Bossel, 1999, p. 9). In the systemic module of this paper, we offer an option for reconciling these two trends. That is, we use indicators for depicting the current state of the system, and we study their relationship either qualitatively (in the participatory approach) or quantitatively (in the expert approach) to obtain a more holistic view of the system. The iteration between the normative module, where the problem definition and definition of the indicator target ranges occurs, and the system module, where the indicators are defined, allows for including both sustainability criteria and the specific problems of the city-region.

Finally, most of the sustainability assessments, especially when they are based on indicator lists such as the Pressure-State-Response frameworks (cf. Linser, 2002), neglect an overarching consistency appraisal of the targets determined for the single sectors. This can lead to target conflicts which arise when stakeholder interests in a specific sector, e.g., economics, dominate the development of a city-region and result in concerns such as environmental quality or social equity being ignored (cf. Campbell, 1996). If these conflicts are not identified and solved, the development of the city-region may be blocked. In the SSP tool, we account for this issue in the integrative module. In this module, conflicts between target ranges are identified and procedures for their solution are provided, so that a concise guideline for taking sustainable decisions is obtained. The strengths of the SSP construction is, on the one hand, that it refers to an established procedure from operations research, which copes with multiattributive tasks (cf. Taha, 1989, p. 30). On the other hand, the tool is consistent with the "principle of optimal allocation". That is, referring to this principle by means of retaining choices and options, the tool recognizes the economic guideline of efficiency, and the political guideline of being bound to multiple stakeholder interests.

Although the SSP tool is depicted as a linear procedure (step 1 to 6), it is evident that it is an iterative one. It can be conceived as an "evaluative spiral" according to the notion of "hermeneutic cycle" (Gadamer, 1961; Stamoulis et al., 2002). The evaluative spiral implies that one has to view an aspect as problematic in order to examine it as problematic. This suggests as "best practice" a continuous mutual adjustment between systemic and normative aspects during the assessment procedure. In a broader view, it also includes an evolutionary continuous reapplication of the tool, taking into account feedback-loops and new perspectives (cf. Meppem and Gill, 1998, p. 128).

6. Conclusions

The goal of this paper was to develop a decision support tool on a theoretical level, which fulfils the requirements of an appropriate sustainability assessment, considering normative, systemic, and procedural aspects. The tool introduced to construct a Sustainability Solution Space for Decision-making (SSP) provides a consistent set of targets considering the systemic relations among the indicators representing the city-region and gives the decision-makers a concise guideline for sustainable decisions. It should overcome the deficiencies of currently used approaches, which determine lists of isolated indicators, neglect a consistency appraisal of the targets to be achieved, and do not utilize the potential of transdisciplinary approaches. Thereby, it contributes to the repeatedly called for extension of Environmental Impact Assessment, Strategic Environmental Assessment, and similar methodologies.

Further research is still needed. First, we will empirically test the tool. It is currently applied to a city-region in Switzerland as well as to the agricultural sector of Switzerland. In the city-regional case, we will apply the two approaches to analyze possible differences in the outcomes of the participatory and the expert approach. Second, this tool could be integrated into a comprehensive planning framework, combining it with scenario analysis, multiattributive evaluation tools, and strategic planning methods. As the challenge of measuring sustainability of city-regions is strongly connected with evaluating policy decisions (impact assessment of policy), a third task would be to apply this tool to political decisions to determine whether they contribute to sustainable development or not.

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