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METHODS

Models for policy-making in sustainable development: The state of the art and perspectives for research

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Abstract

More and more frequently policy-makers are urged to assess the impact of their strategies and policies in terms of sustainable development. This necessitates the use of applied scientific models as tools for identifying and evaluating the likely environmental, economic and social impacts of alternative policies. The objective of this paper is to provide a framework to help decision-makers choose the most appropriate—or the most appropriate mix—of models, by assessing their relative strengths and weaknesses. The paper also allows potential improvements in modeling techniques to be identified. Six modeling paradigms are assessed, both on a general basis and with respect to two specific policy contexts (energy policy, and land use and transport planning).

Keywords: Sustainable development; Modeling; Decision-making; Impact assessment

1. Introduction: a new discipline or renewed modeling practices?

More and more, policy-makers are urged to assess the impact of their strategies and policies in terms of sustainable development[2]. So much so that an—allegedly—new discipline named 'Sustainability Impact Assessment' (SIA) has been created to address these issues (Lee and Kirkptrick, 2000, 2001). A crucial stage in SIA is anticipating the likely economic,

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[2] "Decision makers increasingly seek to design environmental and development policies that will support sustainable development. To support these efforts, practical tools to formulate sustainable development policies and clear methods to assess their acceptability and effectiveness are urgently needed." (Abaza and Baranzini, 2002, p. ix).

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environmental and social impacts of the planned policy. For long-term and complex policy matters, this is only feasible with mathematical or computer-based models. However, there are several different approaches to economic–environmental or integrated modeling and it is not easy for the policy-maker to decide which is the most appropriate for any context. Our objective here is to help users to choose the most suitable modeling tool for a particular sustainable development problem and to better understand what kind of information can be expected from the models. This issue has been remarkably neglected in the literature. The only paper addressing a similar question is that by van den Bergh and Nijkamp (1991) in this journal, but there is no standard procedure for evaluating the strengths and weaknesses of different modeling approaches for sustainable development policy-making. Our contribution is to elaborate a formal methodological framework to tackle this issue and to apply it to existing modeling paradigms and two policy fields.

This problem is a decision-making one. It has to do with the identification of the possible alternatives (the various modeling approaches and tools), the selection of criteria by which to assess them, the assessment itself with respect to the criteria, the weighting of the criteria and, finally, the aggregation of the partial assessment (on each criterion) in an overall assessment. This is, more or less, the way we will proceed in this paper. Several modeling approaches will be assessed in two stages: first with respect to general criteria closely related to sustainable development and then in relation to policy matters (energy and land use and transport policies) considered from a sustainable development perspective. Six modeling paradigms will be assessed, first on a purely a priori and general basis, and then against two specific policy contexts (energy policy, and land use and transport planning).

The paper is organized as follows. We begin by stressing what is specific in sustainable development in order to decide on the most relevant assessment criteria. The modeling paradigms are then compared against these criteria on a purely a priori basis and ranked with respect to their potential performance in dealing with sustainable development problems. The robustness of this ranking is then checked in two concrete policy contexts: energy policy, on the one hand, and land use and transport policy, on the other hand. These policy domains are considered as collections of still more concrete issues (such as resource exhaustion and energy dependency for the energy case), each embodying the essence of sustainability at different levels. The relative fitness of the various modeling approaches to these policy domains is considered as a function of: (i) the degree to which the policy domains embody sustainable development characteristics; and (ii) the degree to which the modeling paradigms are able to deal with these characteristics. Finally, we look at existing modeling practices in the two policy fields in order to see if they confirm our conclusions about the usefulness of the different modeling paradigms.

2. Methodological answers to decision-making in sustainability

Policy-making, as a kind of rational decision-making[3], includes two different types of intellectual activity: knowing and evaluating. Stripped down to its most general characteristics, it requires us to: (i) identify possible alternatives actions, plans or programs; (ii) choose relevant criteria on which to assess their performances; (iii) optionally, weight the criteria in terms of their relative salience; (iv) assess the various alternatives with respect to the criteria; (v) optionally, translate the assessment into a partial utility value; (vi) rank the alternatives with respect to their overall utility; and (vii) choose the best option or, alternatively, re-start the process from the beginning.

In this article we restrict our analysis to the cognitive aspect of sustainable development policy-making, and more precisely to one particular kind of cognitive tool, applied scientific models. The role of these models within the decision-making process is to assess the likely reactions of the system to policy instruments under behavioral and structural constraints. Policy-making for sustainable development constitutes a very special kind of decision-making,

[3] The adequacy of the rational decision-making model as paradigm for decision making in general (Gigerenzer and Selten, 2002) and for policy-making in particular (Fischer and Forester, 1993; Stone, 2002) is disputable. We will not take a stance in this discussion here. It has been dealt within the sustainability impact assessment context in a subtle way by Koernoev (2001), amongst others.

for three reasons. First, the objectives are not given beforehand, the very definition of the goals and objectives being part of the decision-making problem itself. Second, there is no single decision-maker but a plurality of decision-makers, each with his or her own preferences, objectives, expectations and beliefs. Third, the assessment of the costs and benefits is much more difficult for sustainability issues than for normal businesses. This last reason is of particular interest for us and is related to three key features inherent in all sustainability issues, namely the existence of externalities, the existence of uncertainties, and the interplay between human beings and nature.

The first feature, the externalities, may be of different types, such as spatial (e.g. for a global pollutant), intertemporal (e.g. between generations) and social (e.g. between social categories). Hence, sustainable development issues occur when some human groups do not bear the full cost of their production and consumption patterns but pass the costs on to other human groups which are socially, spatially or chronologically distant, without sufficient — if any — compensation. The second feature is the presence of pervasive uncertainties. The more the planned policy is likely to have a long-term and/or unexpected impact, the greater the uncertainties surrounding its cost–benefit balance and the greater the risk that it entails wide-ranging and long-run deleterious consequences. The third key feature is the interplay between natural or environmental processes and human activity, since, in almost every sustainability issue, there is a conflict between human practices and natural processes. Many authors argue that this is the most important—if not the only—meaning of sustainable development[4]. Actually, due to the presence of the two previous features, this third is only one of the characteristics of a sustainability problem. What is crucial for our analysis is that each feature calls for a specific methodological answer, as shown in Table 1. These answers are precisely the criteria we are looking for to assess the fitness of the modeling approaches. It is necessary to specify what sustainable development requires from a modeling perspective, and what conditions must be fulfilled for models to be better suited to sustainable development. Only then will it be possible to compare the strengths and weakness of the various modeling paradigms.

Table 1
From sustainability problems to methodological answers

Problem	Methodological answer
Human–nature interactions	Interdisciplinary approach
Uncertainties	Uncertainty management
Temporal externalities	Long range view
Spatial externalities	Local–global perspective
Social externalities	Stakeholders participation

3. Five methodological criteria

A quick analysis of the most challenging sustainability issues reveals that five methodological criteria must be taken into account: an interdisciplinary approach, uncertainty management, a long-range or intergenerational point of view, ‘glocality’ (Funtowicz and Ravetz, 1990) and participation[5]. These criteria are close to those considered by van den Bergh and Nijkamp (1991).

3.1. Interdisciplinary approach

In the context of applied modeling, ‘interdisciplinary’ means several things. First of all, it means that the model’s state variables must pertain to more than one scientific discipline. Another way of saying this is that it is not enough to take into account the impact of changes in state variables pertaining to a single discipline on, environmental indicators for example, to be credited with an interdisciplinary perspective. A genuinely interdisciplinary model should open the black box between core variables and impact indicators and incorporate the impact indicators into the model’s kernel. In other words, the model should provide for feedback between variables with different ontological natures. Another way to ensure interdisci-

[4] As an example, Van den Bergh and Hofkes (1998) write: “Although the precise definition of sustainable development is subject to different interpretations, it is generally agreed that it refers to the long-term mutual interdependence between resource availability and environmental quality on the one hand and a stable economic development on the other hand”.

[5] An in-depth analysis of these criteria is available in Boulanger and Bréchet (2001).

plinarity is to adopt a meta-theoretical language in which every disciplinary statement can be reformulated. General System Theory (Bunge, 1977) is the most serious candidate for this. It can be seen as a trans-disciplinary framework, i.e. a framework where statements and variables from different disciplines can be integrated, not just put side by side. Moreover, from a pragmatic viewpoint, an authentically interdisciplinary approach requires that the building of scenarios as well as the interpretation of outcomes should result from an interdisciplinary dialogue where all the relevant disciplines have a say.

3.2. Uncertainty

In a modeling context, epistemological uncertainty is threefold: uncertainty about a model's quantities (the parameters and initial conditions); uncertainty about a model's structure (the relations between its variables, functional forms, causal influences, delays, etc.); and uncertainty about a model's pertinence (its level of granularity, selection of variables, closeness, time scale, etc.). Sensitivity analyses and standard statistical methods only help in dealing with quantitative uncertainty. It is also the case for scenarios, defined as sets of coherent hypothesis on the likely values of several quantities taken together. The only way to reduce the two other kinds of uncertainties—except for very recent statistical techniques such as Bayesian model averaging—is to improve our scientific knowledge.

3.3. Long-term perspective

By a long-term perspective we do not mean that models should necessarily adopt a time span of several hundred years. What is more important from a modeling perspective is that various time spans should be fully integrated, and that a time span long enough to allow the unfolding of the systems' complete dynamics (natural cycles, business cycles, etc.) should be adopted. Since what matters from a sustainable development perspective is intra-generational and inter-generational equity, the generation (however defined) is a natural duration unit for sustainability assessment. In economics, overlapping generation models, for instance, are useful in that respect without necessarily adopting a long-term perspective.

3.4. Global–local perspective

The global–local perspective, or glocality for short (Funtowicz and Ravetz, 1990), is related, at the political level, to the well-known motto 'think globally, act locally'. As we have seen, the need to adopt a multi-level stance stems from the fact that spatial externalities are omnipresent. However, from a methodological point of view, it also has to do with the pervading challenge of the micro–macro relationship. In most scientific disciplines—even the most advanced ones such as theoretical physics—there are still no general or fully satisfactory answers to questions such as 'how does the macro-level emerge from micro-level processes?', 'how are the processes at the micro-level shaped or constrained by the macro-level?' and 'what is the relative autonomy of the various hierarchical levels?'.

3.5. Participation

In a purely scientific context, stakeholders' participation cannot be considered as a methodological requirement for modeling activity. But applied modeling in a policy-making context is rather different from pure science. The need for participation in such a context was first advocated some time ago by Bunge (1995), who argued that "the design of any effective economic policy (...) cannot be left in the hands of economic specialists, but should result from a cooperative efforts of experts in a number of related disciplines, as well as representatives of the sectors likely to be affected by the implementation of the plan". This quotation is still more apposite if 'economic' is replaced by 'sustainable development'. For a model to allow for public participation means that it must be as comprehensible as possible, making room for the integration of stakeholders' values and objectives, and facilitating the communication of simulation outputs.

4. Candidate models for sustainable development policy-making

Six kinds of models frequently used in socio-economic policy-making have been selected for consideration in this paper: macro-econometric models, computable general equilibrium models, optimization models, system dynamics models, probabilistic or Bayesian network models (this category also includes risk assessment models based on influence diagrams), and multi-agent simulation models. The first three kinds are mainstream, well-known economic or engineering models widely used in policy-making. The last three are less common, except perhaps for system dynamics models which are commonplace in environmental science and natural resources management. Let us briefly describe the main properties of these models.

(1) Macro-econometric models have been intensively used for about twenty-five years for simulating national economies to forecast short- or medium-term profiles and to assess economic policies. A macro-econometric model is a simulation system of simultaneous equations (generally with a neo-Keynesian flavor) validated by statistical procedures on time-series or cross-sectoral data. They have been extended to incorporate environmental dimensions, especially via energy consumption and production (see, for example, with the European HERMES model (EC, 1993), NEMESIS[6] and INTERLINK[7]).
(2) Computable general equilibrium (CGE) models are based on neo-classical economic theory. National economies are pictured as systems of interrelated markets in equilibrium, prices ensuring the clearing of demand and supply in each of them. As with macro-econometric models, the interrelationships between productive sectors are expressed by way of an input–output matrix but, unlike macro-econometric models, CGE models are calibrated rather than empirically validated. CGE models are long-term oriented and their main purpose is policy analysis, not forecasting. The European GEM-3[8] model is a well-known example of CGE modeling in energy-economy, as are EPPA[9], GTAP[10] and MERGE[11].
(3) Centralized optimization models are mainly dedicated to decision-making on the choice of technology: given an objective function (generally the minimization of operational and fixed costs) and some constraints on technological availability, prices, etc., the model identifies which technologies should be chosen to get as close as possible to the objective. Thus, optimization models are intrinsically normative, not descriptive like simulation models. A representative example is MARKAL-TIMES[12] for energy policy.
(4) We include in the system dynamics category all models based on general system theory. Actually, most system models in the literature are expressed in terms of levels (stocks), rates (flows) and auxiliaries i.e. in the 'Forresterian' dialect of general system theory. This is probably because the most widespread and least expensive system simulation softwares (Stella[13], Powersim[14], Vensim[15] etc.) are based on this dialect. The system dynamics approach is much more popular in environmental sciences than in economics or political science where it suffers from a bad reputation due to some early unscrupulous applications. However, systems dynamic models have many applications in management sciences (Sterman, 2000), and in climate and energy policy (Fiddaman, 2002).
(5) Multi-agent simulation is quite a new approach in modeling. It is very different from other kinds of models insofar as it is not expressed in terms of variables, functions or equations but in terms of agents, objects and environments. The building blocks of multi-agent models are autonomous entities interacting with each other and with an artificial environment. Multi-agent models are sometimes depicted as artificial societies (Epstein and Axtell, 1996) or artificial ecosystems. Many applications of multi-agent modeling can be found in the on-line Journal of Artificial Societies and Social Simulation[16].

[6] URL: http://www.nemesis-model.net.
[7] URL: http://www.olis.oecd.org/olis/2001doc.nsf/linkto/eco-wkp(2001)32.
[8] URL: http://gem-e3.zew.de/.
[9] URL: http://web.mit.edu/globalchange/www/eppa.html.
[10] URL: http://www.gtap.agecon.purdue.edu/.
[11] URL: http://www.stanford.edu/group/MERGE/.
[12] URL: http://www.etsap.org/markal/main.html.
[13] URL: http://www.iseesystems.com.
[14] URL: http://www.powersim.no.
[15] URL: http://www.vensim.com.
[16] Available at http://jasss.soc.surrey.ac.uk/JASSS.html.

Table 2
Scale for pair-wise comparisons on sustainability criteria

Value	Meaning
1	As good as
3	Slightly better than
5	Significantly better than
7	Much better than
9	Absolutely better than
2, 4, 6, 8	Intermediate values

(6) Bayesian networks (Jensen, 1997) are risk assessment models based on influence diagrams (acyclic directed graphs) and probability theory. The combination of a graphical representation of causal chains between events or variables and an inference mechanism enabling information processing from (the probability of) causes to (the probability of) effects (or the other way round) makes the Bayesian network a convenient tool for various tasks such as early warning, diagnosis, prediction, and simulation in a probabilistic framework. Applications of Bayesian networks to food security and famine early warning can be found in Boulanger et al. (2004) and to land use management in Bacon et al. (2002). However, the most widely used, but largely unnoticed, Bayesian network is Microsoft's Office help system.

5. Analysis of the goodness-of-fit between models and sustainable development

5.1. The method

In order to assess the relative effectiveness of the different kinds of models in dealing with policy issues in a sustainable way, we need to know: (i) their general adequacy with respect to each of the criteria, independent of the context of the application; (ii) the importance of each criterion for the policy issue under consideration. The reasoning is then as follows:

if model M is effective in handling criterion C,
and if criterion C is important for policy matter P,
then model M is effective for assessing policy P.

More precisely, because we are dealing with relative, not absolute, appropriateness, we have:

Stage 1 if model M_1 is better than model M_2 in handling criterion C,
Stage 2 and if criterion C is important for policy matter P,
Stage 3 then model M_1 should be preferred to M_2 for assessing policy P.

Therefore, three stages have to be considered. We must assess the suitability of the different modeling paradigms for handling the sustainability criteria (Stage 1); evaluate the degree to which sustainability is important for the policy issues being considered (Stage 2); and infer from Stages 1 and 2 the relative effectiveness of the modeling approaches to the policy domain (Stage 3). Let us now describe each stage in detail.

In Stage 1, the effectiveness of the different modeling paradigms is estimated by pair-wise comparisons as in the AHP decision-making method. Formally, let $M=\{M_1,M_2,\ldots,M_m\}$ be the set of m models to be assessed and $C=\{C_1,C_2,\ldots,C_n\}$ the set of n criteria. For each C_k we compare each model M_i to each other model M_j using the scale displayed in Table 2.

If the modeling approach M_i is considered much better than model M_j with respect to the criterion C_k, then we have $\alpha_{ijk}=7$. Because it is a reciprocal relationship, model M_j is automatically rated much worse than M_i, and we have $\alpha_{jik}=1/7$. Therefore, we only need to perform $[m \cdot (m-1)]/2$ comparisons. For each criterion, we end up with the matrix represented in Table 3.

Table 3
Example of a pair-wise comparison of models on the interdisciplinarity criterion

	MA	DS	RB	OC	EG	ME	SUM	NORM
MA	1.000	1.000	2.000	5.000	3.000	3.000	15.000	0.288092
DS	1.000	1.000	2.000	5.000	3.000	3.000	15.000	0.288092
RB	0.500	0.500	1.000	3.000	2.000	2.000	9.000	0.172855
OC	0.200	0.200	0.333	1.000	0.500	0.500	2.733	0.052497
EG	0.333	0.333	0.500	2.000	1.000	1.000	5.167	0.099232
ME	0.333	0.333	0.500	2.000	1.000	1.000	5.167	0.099232
							52.067	1

Table 4
Relative strengths and weaknesses of various modelling approaches with respect to criteria for sustainable development policy-making

	Interdisciplinary potential	Long-term, intergenerational	Uncertainty management	Local–global	Participation	Ranking
Multi-agents	0.29	0.27	0.30	0.34	0.40	1
System dynamics	0.29	0.27	0.08	0.11	0.20	2
Bayesian networks	0.17	0.07	0.39	0.17	0.13	3
Optimization	0.05	0.07	0.06	0.17	0.08	6
General equilibrium	0.10	0.21	0.08	0.11	0.08	4
Macro-econometric	0.10	0.10	0.10	0.09	0.10	5

The last column shows the normalized row sums [17] which express the relative adequacy of the model to the criterion. The more it outperforms the others, the higher its value. Putting together the normalized row sums of all the partial matrices we get the overall matrix (see Table 4). Here too, a ranking of the modeling paradigms is computed from the normalized row sums.

The second stage consists of computing the importance of the different criteria in the policy domain under consideration. This is done by decomposing it into its most important sub-domains or *problematics* and assessing the importance of the criteria for each of them, as shown in Table 5 below (for the land-use case). It was impossible to follow the AHP technique of pair-wise comparisons here because we wanted to involve several experts and decision-makers in the exercise. A pair-wise comparison of some 7 sub-domains on 5 criteria by about 15 participants would have been too time-consuming and cumbersome a task. Therefore, the values were obtained by direct weighting during a workshop.

Stage 3 consists of combining the information from Tables 4 and 5 to assess the appropriateness of the different kinds of model to the sustainability issues composing the policy domain. This is done by considering the matrices in Tables 4 and 5 as fuzzy matrices expressing fuzzy relations.

It is now well-known that a fuzzy set is a set in which (contrary to a crisp set) elements do not have a 'yes or no' membership but a 'more-or-less' one. That is, the membership of an element in a fuzzy set is a real number in the [0,1] interval. A fuzzy relation R from set X to set Y (or between X and Y) is a fuzzy set in the direct (Cartesian) product $X*Y=\{(x,y)| x\in X, y\in Y\}$ characterized by a membership function μ_R such that $\mu_R=X*Y\rightarrow[0,1]$. Given finite sets $X=\{x_1, x_2 \ldots x_m\}$ and $Y=\{y_1, y_2, \ldots y_n\}$ a fuzzy relation in $X*Y$ can be expressed by an $m*n$ fuzzy matrix.

Table 4 displays the fuzzy $(m*n)$ matrix MC expressing the fuzzy relation 'appropriateness' (R_1) between the set M of m modeling tools and the set C of n criteria. For example, the cell (3,3) of Table 4 can be read as: 'the model <Bayesian networks> is appropriate to the criterion <uncertainty> with membership 0.39'. Table 5 shows the fuzzy $(n*p)$ matrix CP expressing the fuzzy relation 'importance for' (R_2) between the n criteria and the p policy issues.

Finally, we combine the two matrices. Given a fuzzy relation R in $X*Y$ and another fuzzy relation S in $Y*Z$, the composition of R and S, denoted $R\bullet S$, is a fuzzy relation in $X*Z$ whose membership function is given by the fuzzy counterpart of matrix multiplication on matrices X and Z. In our case, the relation R_3 (effectiveness for) is the composition of R_1 (adequacy to criteria) and R_2 (importance for) whose corresponding matrix MP is given by multiplying matrix MC (Table 4) and matrix CP (Table 5). In short,

$MP = MC\bullet CP$, • being a fuzzy operator corresponding to matrix multiplication.

Fuzzy set theory offers several possibilities for the • operator, the most commonly used being the 'max–min' and 'max–product' operators. The 'max–min' operator is equivalent to matrix multiplication except that, instead of forming the product of terms, their

[17] The standard AHP procedure consists in normalizing the principal eigenvector. The geometrical means of the row values are generally a good approximation to the values of this eigenvector. In our example, the row sums are very close to the geometrical means so we decided to use them.

Table 5
Relative importance of criteria for each system or problem in land use

	Interdisciplinary potential	Long-term, intergenerational	Uncertainty management	Local–global	Participation
Energy	0.21	0.23	0.14	0.19	0.23
Biodiversity	0.17	0.17	0.26	0.23	0.17
Water	0.23	0.23	0.15	0.19	0.19
Transport	0.17	0.24	0.15	0.15	0.29
Poverty, exclusion	0.20	0.20	0.15	0.20	0.25
Health, safety, well-being	0.21	0.19	0.19	0.19	0.23
Amenities	0.20	0.29	0.10	0.12	0.29
Ranking	3	2	5	4	1

minimum value is taken and, instead of summing them, their maximum is taken. Formally,

$$\mu_R \bullet_S(x,y) = \max[\min(\mu_R x, y)(\mu_S y, z)].$$

The max–product operator is defined as:

$$\mu_R \bullet_S(x,y) = \max[(\mu_R x, y)^*(\mu_S y, z)].$$

Table 6 shows the outcome of the application of the max–product operator to Tables 4 and 5.

To summarize, the method is a pragmatic mix of different techniques. The pair-wise comparisons of alternatives on the 1–9 ratio scale are taken from the Analytical Hierarchy Process. It was the most convenient for computing the matrix in Table 3 because only two experts were involved and only 6 * 15 comparisons had to be made. However, with many experts and more numerous comparisons, such a technique would have been too demanding. The technique for inference in Stage 3 is known in the fuzzy system literature as the 'compositional rule of inference'. The underlying 'philosophy' is from fuzzy logic. The pair-wise comparison technique and the direct weighting methods used in Stages 1 and 2 must be understood as convenient ways to elicit the membership functions of the fuzzy relations.

5.2. Interpreting the results

The effectiveness of the different modeling approaches is synthesized in Table 4 on an a priori basis, i.e. independently of the policy context. Before discussing the results, it is crucial to keep in mind that this ranking was done with regard only to the five criteria mentioned above. Models that may look promising here could well appear seriously flawed if they were assessed on other methodological or epistemological criteria.

Table 4 shows that, regardless of the policy issue considered, the multi-agent approach is the most promising. Its strength comes mainly from its purely 'bottom-up' character, a feature which no other models in our selection show. It is also the best suited to the representation of interactions between agents and their (natural or social) environment and therefore has a very powerful interdisciplinary potential. Because it is a fundamentally stochastic approach, it can make room for and manage uncertainties. The realism of the representation of the agents and the environment—compared to the abstract aggregated variables used in other models—may ease the appropriation of the model by stakeholders and, therefore, their participation. Its capacity to generate a long-term perspective

Table 6
Relative fitness of modelling approaches to land use policy-making in a sustainable development perspective

	Energy	Biodiversity	Water	Transport	Poverty	Health	Amenities	Ranking
Multi-agents	0.11	0.10	0.11	0.12	0.10	0.09	0.14	1
System dynamics	0.06	0.05	0.07	0.07	0.06	0.06	0.07	3
Bayesian networks	0.05	0.09	0.05	0.07	0.06	0.06	0.07	2
Optimization	0.02	0.02	0.02	0.02	0.02	0.02	0.02	5
General equilibrium	0.03	0.03	0.03	0.03	0.02	0.02	0.04	4
Macro-econometric	0.01	0.02	0.01	0.01	0.01	0.02	0.02	6

comes from the fact that it models the succession and overlapping of generations of agents very naturally.

Bayesian networks are excellent on uncertainty management and have a good interdisciplinary potential. If a variable can be expressed as a probability distribution, it can be included in a Bayesian model whatever its ontological nature. We think that the graphical representation of the hierarchy of causes and effects will help the stakeholders to grasp the main features of the model and thus foster their participation. It is, however, much weaker than the multi-agent approach with regard to long-term perspectives, even though there is room in Bayesian networks for a limited representation of temporal dynamics.

System dynamics models are strong on 'interdisciplinarity' and long-term perspectives. They are weaker on 'glocality' because of their very aggregated nature. The participation of stakeholders has always been considered a must by the founding fathers of system dynamics.

Except for CGE models on the intergenerational criterion, all the more traditional kinds of model are at best average on our criteria; sometimes they are simply weak. However, let us repeat here that this does not mean that they are fundamentally flawed, useless or inadequate. Instead, it indicates that there is room for improvement in their methodology in order to match a sustainable development perspective better.[18]

This assessment is a priori, i.e. based on an abstract analysis of the general features and properties of the different modeling paradigms. Let us now adopt a more concrete perspective and look at these methodologies at work in a real policy-making context. Two public policies sectors have been selected as case studies: land use and transport on the one hand and energy on the other hand. These two issues will be considered in the two following sections.

6. A first application: land use and transport

The sustainability impacts of land use policies are numerous and all-inclusive. Almost every decision concerning changes in land use has economic, environmental and social consequences. It impinges on such environmental and socio-economic systems as water, soil, air, biodiversity, transport, energy, human health, safety and well-being, social stratification and poverty, and amenities. An impact assessment of land use policies on each of these different systems or problems calls for an interdisciplinary standpoint, uncertainty management, long-term perspectives, 'glocality' and participation. Yet, it remains true that some uses demand more from some factors than others or, to put it another way, that not every criterion has the same importance for each of these systems or problems. Of course, it is a very difficult task to assess the relative importance of each criterion for each system. The scores displayed in Table 5 are the outcome of a participatory exercise, a deliberation between scientists from various disciplines and public servants from different administrative departments. They are tentative and ought not be taken as definitive. Moreover, the figures have no value as such, only the relative ranking of criteria and systems/problems, as expressed by them, should be considered.[19]

A comparison of the row totals[20] gives us a relative ranking of problems and systems with respect to sustainable development. Thus, water management and biodiversity (from a land-use policy point of view) may be considered as highly representative of sustainable development problems in so far as they score highly, on average, for each criterion. Inversely, poverty is a less typical 'sustainable development' problem (from a land use policy standpoint).

The comparison of the column totals gives us 'importance weights' for the different criteria from a sustainable land-use policy perspective. The most important criteria are the participation of stakeholders, a long-term perspective and 'interdisciplinarity'. The importance of participation makes sense, in that land-use decisions are the only ones systematically open to public deliberation at several institutional levels.

As explained above, the relative appropriateness of the various modeling approaches to a concrete sustainable development policy domain can be inferred from their ability to handle the general features of

[18] Exploring these themes is beyond the scope of this article; see Boulanger and Bréchet (2003) for a full discussion.

[19] Detailed information on the derivation of these results and their participatory component are available from the authors on request. The final research report is available (in French) on: www.iddweb.be.

[20] Not reported here, the table having been normalised with respect to the sum of each row.

sustainability problems and from the degree to which the given policy domain embodies these sustainability features. Table 6 presents the relative fitness of the modeling approaches to sustainable land use and transport policy. Here again the figures are significant only at an ordinal level of measurement. However this is all that is needed to rank the different methodologies, as is done in the last row using the normalized column totals. It is not surprising that multi-agent simulation modeling appears to be the most promising approach. They are followed by Bayesian networks and system dynamics (with similar ranking) and CGE models. Macro-econometric and optimization models appear to be less productive from a sustainable development point of view in that issue.

6.1. Current practices in land use and transport modeling

Do current modeling practices in the field corroborate these conclusions? They certainly do as far as centralized optimization methods are concerned: with the exception of a couple of transport-only models, such models are almost non-existent in studies of land use. This is also true for Bayesian networks, perhaps because of the novelty of this approach. There are no pure macro-econometric or CGE models of land use and transport, but many models combine these two methodologies. The most widely used tools (such as TRANUS[21], MEPLAN[22], DRAM/EMPAL (Putnam, 1992) and IRPUD[23]) combine macro-econometric tools (input–output matrices, random utility models, entropy maximization, etc.) and a spatial (partial) equilibrium framework. They are definitely state of the art in the field but have some acknowledged weaknesses, notably with respect to ‘interdisciplinarity’. Indeed, most land use and transport models are very weak in integrating water management, biodiversity impacts, health, well-being and poverty considerations. Energy is the only domain which is not purely economic that they integrate more or less satisfactorily. This is a recognized problem, to the extent that the European Commission has commissioned two important research projects to try to improve the capabilities of these models in tackling the environmental and social impacts of land use and transport. The SPARTACUS and PROPOLIS[24] projects aim at integrating social, environmental and economic indicators into the MEPLAN model so as to assess the sustainable development impacts of land use policies. However, the simple addition of output indicators does not match our definition of ‘interdisciplinarity’ as allowing feedback between state variables of different ontological natures.

The capabilities of the mainstream models are also rather limited with respect to the long-term criterion. The way they are identified and calibrated makes them very dependent on the initialization data and their fundamental structure (which is based on a spatial equilibrium hypothesis in a comparatively static situation) is much more suited to short- or, at best, medium-term than to long-term assessment.

A more promising modeling approach with respect to these issues is the one taken by URBANSIM (Waddell, 2002). This is a disaggregated non-equilibrium dynamical framework which approximates more and more closer as time goes by to micro-simulation (like IRPUD), or even to agent-based models. However, it still makes use of random utility functions, input–output matrices, etc., like more traditional spatial economic models.

System dynamics models originate in Forrester’s renowned theories of urban dynamics (Forrester, 1969). One of the most foolhardy features of Urban dynamics was its disdain for any established academic knowledge—even though it appears to have been influenced by old-fashioned economic theories such as Kondratiev’s cycles—and its reliance on experts and practitioners’ knowledge. Forrester is certainly one of the first and most thorough-going advocates of stakeholder participation in model building. Accordingly, the model is more a disciplinary than interdisciplinary; we could even say that it is trans-disciplinary. It also adopted a very long-term perspective (250 years), a time-scale deemed necessary to picture the growth, stabilization and decay of cities. As for uncertainty management and local/global interactions, the case study confirms the a priori assessment displayed in Table 4: Forrester’s model is average if not weak with respect to these criteria.

[21] URL: http://www.modelistica.com.

[22] URL: www.meplan.de.

[23] URL: http://www.raumplanung.uni-dortmund.de/irpud.

[24] URL: http://www.wspgroup.fi/lt/propolis.

Table 7
Relative importance of criteria for each topic in the energy issue

	Interdisciplinary potential	Long-term, intergenerational	Uncertainty management	Local–global	Participation
Exhaustible resources	0.15	0.31	0.23	0.26	0.05
Nuclear power	0.23	0.23	0.23	0.15	0.15
Renewable resources	0.22	0.26	0.13	0.17	0.22
Acces to energy utilities	0.19	0.19	0.19	0.25	0.19
Climate change	0.22	0.22	0.22	0.22	0.11
Rational use	0.22	0.17	0.11	0.22	0.28
Health	0.24	0.24	0.24	0.18	0.12
Ranking	2	1	4	3	5

However, there is a new and more accurate land use and transport interpretation of system dynamics, the UGROW model[25] from the Prescott College NASA Program. This is built upon three main sub-systems: economic, socio-demographic and environmental. It deals with the quality of life, employment, industrial and commercial activities, land use, housing, transport, energy, pollution, etc. The time span considered is impressive: from 1950 to 2100. Thus, the general strengths of system dynamics models are also UGROW's strengths.

Agent-based models or multi-agent simulation, although new to the modeling community, are becoming more and more common in land use and resource management. More theoretically or policy-oriented models (such as ABLOom (Otter et al., 2001), CIRAD's models (Bousquet et al., 1999) or the PolSim software tool[26], respectively), do display the strengths identified in Tables 4 and 6: interdisciplinary potential, local–global interaction modeling and stakeholder participation.

Thus, a more detailed analysis of several modeling tools employed in land use and transport policy making reveals the same strengths and weaknesses of the various approaches as the first stage of our assessment. However even the weakest of them has something to commend it for sustainable development, insofar as it is linked to a Geographical Information System (GIS). The explicit modeling of space and land with a GIS opens the way to an easy integration of discourses and viewpoints. It allows the translation of rather abstract objects (systems, processes, and attributes) into concrete entities and gives a vivid representation of them as buildings, rivers, open spaces, roads, etc. This makes it easier for stakeholders to participate in the building of scenarios about possible land uses and in the analysis of the simulations' output.

7. A second application: energy

The topic of energy has, over the years, given rise to a large number of studies on related subjects of concern. The recent outlook by the European Commission (2003) provides good examples of the issues at stake and of the ways they can be considered from a policy viewpoint. However, the analysis of the implications of these issues in terms of sustainable development policy-making remains scarce. In our methodological framework it is necessary to disentangle the issues at stake within the energy debate. We considered the following: exhaustible resources, nuclear power, renewable resources, access to energy utilities, climate change, rational use of energy, and the impact on health. As for the land use policy issue, the key point in our methodology is that some of these issues are more demanding than others on some criteria, and that each criterion does not have the same importance for each of these issues. Both of these questions are considered from a sustainable development perspective. As for the land use case, the scores in Table 7 come from a participatory exercise, but should be taken as mainly indicative.

Interestingly, this table shows that four criteria (interdisciplinarity, long-term perspective, uncertainty, and local–global) seem more important for this issue than for land use. Yet this is balanced by a decrease in the relevance of participation. Admittedly, participation does constitute one of the key points in land use

[25] Now called SCALE, see the URL: http://zenith.geog.ucsb.edu/.
[26] It seems to have recently changed its name to "Scenario 360"; see http://www.communityviz.com.

Table 8
Relative fitness of modelling approaches to energy policy-making in a sustainable development perspective

	Exhaustible resources	Nuclear power	Renewable resources	Acces to energy utilities	Climate change	Rational use	Health	Ranking
Multi-agents	0.09	0.07	0.09	0.09	0.08	0.11	0.07	1
System dynamics	0.08	0.07	0.07	0.05	0.06	0.06	0.07	3
Bayesian networks	0.09	0.09	0.05	0.07	0.09	0.04	0.09	2
Optimization	0.04	0.03	0.03	0.04	0.04	0.04	0.03	5
General equilibrium	0.06	0.05	0.05	0.04	0.05	0.04	0.05	4
Macro-econometric	0.03	0.02	0.03	0.02	0.02	0.03	0.02	6

practices, whereas this is far from true for energy issues (which are generally considered as engineering matters for which participation is irrelevant).

Table 8 presents the outcome of the fuzzy matrix operator combining Tables 4 and 7. It displays the relative ability of the different modeling approaches to tackle the sustainable dimensions of the energy issue. We will focus here on the ranking of the modeling approaches [27]. The overall ranking of models is the same as for land use, but for different reasons. For example, multi-agent models do not give the best fit for all the topics here, but they provide the best compromise. All in all, one conclusion does emerge, as for the land use issue: the most specialized modeling approaches used in the context of the current policy debates remain one rung behind the most appealing approaches from a sustainable development policy standpoint. This raises the twin questions of the opportunity and the cost of tailoring the modeling frameworks to the policy debate over sustainable development.

8. Conclusion

As far as we know, there is at present no standard procedure for evaluating the strengths and weaknesses of different modeling approaches for sustainable development policy-making. The modus operandi adopted here was loosely inspired by multi-attribute utility theory (MAUT). In short, MAUT consists in selecting a set of relevant criteria (attributes), giving each criterion an importance weighting and then rating each alternative with respect to the criteria. If there are many decision-makers, the individual ratings are then aggregated. Finally, the ratings are once again aggregated (by addition, multiplication or whatever) across the various criteria weighted by their relative importance.

Here, we have drawn attention to five methodological attributes of equal importance which are central to sustainable development decision-making: interdisciplinary potential, long-term and intergenerational concern, uncertainty management, local−global interaction, and stakeholders' participation. The following modeling paradigms have been scrutinized: macro-econometric models, computable general equilibrium models, optimization models, system dynamics models, multi-agent simulation models and Bayesian network models. All have been rated on an ordinal scale during participatory workshops attended by model users and builders. What is innovative is the way we then proceeded to assess the potential of the six alternatives for policy decision-making in energy and land-use issues.

What emerges is that not all modeling approaches are equally helpful for sustainable development policy-making. Most importantly, we provide a rationale for our ranking. Naturally, every model has its own utility, and the one-size-fits-all model will never exist. What is important is to understand both how the models could be improved for sustainable development purposes and used in support of decision-making. In this respect, the models considered in this paper can be split with respect to their degree of involvement in the decision-making process to date. The evidence that the most intensively used are not the most suitable for sustainable development purposes suggests twin channels for research: firstly, how to use the best-performing models in the decision-making process; and, sec-

[27] Extensive analyses of these matrices are available in our final research report (Boulanger and Bréchet, 2003).

ondly, how to improve the goodness-of-fit of the modeling tools that are currently used. Our methodology may help in identifying the key features for further research.

Unambiguously, the most promising modeling approach seems to be the multi-agent simulation model. It has many potential strengths to commend it. First of all, such models bypasses most mathematical jargon and simulate scientific hypotheses or even commonsense knowledge directly, without prior mathematical translation. Second, they allow for an intuitive representation of the environment and of the embedding of agents in a spatial and natural setting. Finally, they really display a 'bottom-up' structure, thus allowing an adequate representation of micro/macro relationships. Admittedly, multi-agent modeling represents a new paradigm and many theoretical and methodological problems remain to be resolved before it can be used on a regular basis for practical sustainable development policy-making. However, several powerful and user-friendly computer software for building agent-based systems are already available, some of them for free (e.g. Ascape[28], Netlogo[29] and RePast[30]). It is our opinion that public scientific and R and D policy-makers and advisers should foster their development and use in universities, schools and research institutions.

Bayesian networks and system dynamics should also be more widely diffused. What makes them attractive from a sustainable development point of view is the fact that they combine an intuitive graphical user interface with an interdisciplinary or trans-disciplinary scientific language (Bayesian or subjective probability theory for Bayesian networks and general system theory for system dynamics). The graphical interface helps to translate stakeholders' knowledge and beliefs into workable equations or statements, while the universal language fosters dialogue between different scientific disciplines.

To conclude, what is common to Bayesian networks, multi-agent simulations and system dynamics models that makes them relatively well-suited to sustainable development is their potential for cognitive integration, i.e. the integration of various kinds of knowledge, various scientific disciplines, different time-spans and different institutional and ontological levels. Such integration typically underpins modeling tools which are suitable for decision-making in sustainable development.

[28] URL: http://www.brook.edu/es/dynamics/models/ascape/.

[29] URL: http://ccl.northwestern.edu/netlogo/.

[30] URL: http://repast.sourceforge.net/.

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