Setting concepts into motion: improving scientific tools in support of sustainable development decision-making

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Introduction

More and more awareness has grown that the developed world cannot continue to produce and consume as used to and that the developing world should not apply the same development model as the developed world.

The European Commission, countries and regions committed in one way or another, very strongly or moderately to a development agenda that meets the goals of sustainable development in policy development and implementation. In this context, it is widely recognised in the European Union that the requirements of sustainable development should be taken into account in decision-making. The European Commission wants to ensure that all major policy proposals include an assessment of sustainability impacts, which means striking and maintaining the right balance between the social, economic, and environmental dimensions. Clearly, sustainable development has been given a prominent place on the EU political agenda in recent years.

There is a need to determine which instruments are best suited for conducting sustainability research and to identify priority issues for the networking of national R&D programmes. The European Commission is pursuing these aims and is notably questioning R&D policy-makers about how to integrate sustainability into their research projects and programmes.

At the Bonn workshop "Setting concepts into motion - sustainable development and R&D policies", held in February 2001, representatives of countries, international organisations, and the Commission presented sustainable development research activities and discussed sustainability research. They identified several thematic areas that could be addressed by short-term research. Another meeting held in Stockholm ("Bridging the Gap", in May 2001) focused specifically on integrating sustainability into different policy sectors. The discussions demonstrated the need to establish a common scientific and technical reference system for policy support in Europe, as advocated by the IPTS (2001). Broadly speaking, this system should have two roles: translating relevant knowledge to policymakers and stakeholders and assessing the impacts of policy options on sustainability.

Clearly, sustainable development policies need to be scientifically underpinned by adequate scientific supporting tools and methodologies.

As soon as we focus on sustainability, the problems to be dealt with become particularly intricate, given their global context, the complexity of the systems considered, and their different space and time scales (global *versus* local, short term *versus* long term). There are risks and uncertainties, conflicting values, high stakes (threshold effects), and an urgent need to make decisions. It is necessary to ensure more transparency, to promote stakeholder participation in both policy-making and research, to apply the precautionary principle, and to integrate economic security, ecological integrity, and social equity... All these challenges require new scientific tools and new decision-making practices.

In summary, scientific tools for sustainability assessment should:

- be multidimensional and interdisciplinary,
- incorporate the precautionary principle,
- take system complexity into account,
- be useful both in setting long-term goals and in providing policymakers with timely answers,
- integrate stakeholders from the inception phase of research and policy-making,
- be transparent and participatory.

This booklet proposes a generic methodological framework for dealing with these issues. It highlights five criteria that any approach to sustainable development should meet: (1) interdisciplinarity; (2) taking uncertainties into account; (3) a long-term perspective; (4) inclusion of both global and local dimensions; (5) stakeholder participation. The core of our research is, on the one hand, to check the capacity of the tools used in decision-making to incorporate these criteria and, on the other hand, to specify the role of each kind of tool in the decision process. Obviously, the tools cannot be considered separately from the decision-making process. This means that to tackle sustainability issues in policy making requires improving both the scientific tools and the decision-making process.

This booklet is organised as follows. The first two sections present the material on which we shall base our discussion. The first discusses the five criteria and their methodological implications for decision-making, the second analyses the decision-making process itself and the role each kind of tool is expected to play. The next two sections tackle the main models used in decision-making, their theoretical properties, strengths and shortcomings, and their capacity (effective and potential) to meet our criteria in the perspective of elaborating a sustainable development policy. It will be shown how integrated assessment approaches explicitly try to incorporate sustainability criteria and why they can be seen as proof that no single tool can cope with sustainability issues. [1]

1. Criteria for sustainable development decision-making

The intrinsic complexity of sustainable development issues is often pointed out. As explained by van den Bergh and Hofkes (1998), for example, the problem amounts basically to addressing the complexity of relationships between the actors and components of the economy-environment-institution system over time. A limited number of criteria are systematically used to characterise these relationships. These criteria and their intricacy highlight why sustainable development should be treated differently from most traditional matters of concern.

The literature on sustainable development and modelling shows five typical aspects of tackling sustainable development: interdisciplinarity, uncertainty, a long-term perspective, both global and local dimensions, and stakeholder participation. We argue that any comprehensive model designed to support the elaboration of a sustainable development policy should include these five aspects. Formally, this means finding technical solutions for implementing all five of these criteria mathematically within the models. It is important, however, to carefully consider the meaning of each criterion.

1.1. What is interdisciplinarity?

Achieving sustainable development is originally viewed as striking a suitable balance between the economic, social, and environmental dimensions of development (the "three pillars"). Scientifically, interdisciplinarity means that any comprehensive analysis of a sustainable development issue requires insights from several scientific disciplines, belonging to both the natural and the social sciences (physics, biology, sociology, economics, politics, demography, etc...). The level of integration between the different disciplines (the degree of interdisciplinarity) depends on the subject matter. More interdisciplinarity is certainly also needed if sustainable development is viewed as a process where the various forms of productive capital must stay in line with each other. By this we mean production-derived assets, of course, natural assets, and also human and social assets. These specific assets together

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form the productive base of any society. For development to be characterised as sustainable, this base must be maintained, without declining, from generation to generation (Dasgupta and Mäler, 2000). This notion of a non-declining overall productive capacity leads us to the fundamental and difficult issue of trade-offs between one type of asset and another and of the limits to such trade-offs. Clearly, this cannot be considered without a better understanding of the dynamic interactions and feedbacks between natural and socio-economic systems.

Interdisciplinarity may be the criterion that tools and models most often claim to meet. This may reflect the difficulty of identifying whether a tool is interdisciplinary or not and to what extent it deserves the 'label'. For researchers and practitioners, a tool or model often becomes interdisciplinary as soon as productive collaboration takes place with other scientific fields. It would be preferable to call this multidisciplinarity. To be truly interdisciplinary, a methodology requires at least two features: (1) the existence of formal feedback between the different fields considered in the system (for example, feedback between the environment and the economy, with full cost pricing or health impacts) and (2) grouping and integration of many theoretical paradigms into a comprehensive formal framework.

1.2. What is uncertainty?

The fact that decision-making involves many uncertainties is far from new (Funtowicz and Ravetz, 1990). There are numerous sources of uncertainty stemming from imperfect knowledge of the initial system and of the impacts of the policies considered (Handmer *et al*., 2001). Threshold effects and irreversibility can reinforce the consequences of a policy and entail excessive social and economic costs if they are not correctly anticipated. In decision theory, we speak of 'risk' when the probability distribution of outcomes is known; when it is not, we speak of 'uncertainty'.

Basically, uncertainty may result from two sources: the information set used by the tool and the state of knowledge of the system considered (formally, the nature and valuation of relationships). Sensitivity analyses are used to address the first problem. These tests can be applied either to the coefficients or parameters of the system or to the data themselves. They can be carried out locally (on a limited number of parameters) or globally (on the whole system). They can also be either deterministic or stochastic; in the latter case, a probability distribution is required. In the best methodological case, these tests indicate the level of confidence associated with a result. Depending on the discipline, such sensitivity analyses are more or less widespread or elaborate. Whatever the methodology used, they serve to identify the sources of uncertainty and to evaluate their impacts on the issue considered.

As a matter of debate, uncertainty directly implies associating the stakeholders with the decision-making process (see participation criterion).

Generally, the implications of irreversibility and thresholds are ignored and these shortcomings must be kept in mind. They represent two key dimensions in environmental issues and should really be taken into account in the decision-making process. From this standpoint, they are fundamentally associated with the precautionary principle (Perrings, 1991).

1.3. What is a long-term perspective?

Sustainable development is expected to be a development that lasts. At first sight, this can be understood as the need for a long-term perspective, for example concerning the management of exhaustible resources or demographic trends. A long-term perspective also introduces the fact that several phenomena (climate, population, technical progress, internet technologies...) evolve asynchronously over very different time-scales. Methodologically, this makes implementing the long-term dimension in models a very complex task, particularly in the area of sustainable development, where considering the long term implies taking other criteria into account as well (uncertainty, globality, interdisciplinarity).

The long term is more than simply a question of time. It also raises the question of intergenerational equity (as stated in the Brundtland Report's definition of sustainable development). The intergenerational equity dimension is generally ignored in applied models, except in some computable general equilibrium models. The latter models distinguish different generations and wealth transmission between them. They directly address the question of discounting the future and of choosing an adequate principle of justice (utilitarian, communitarian, Rawlsian...) Hence, real integration of the long-term dimension would involve feedbacks between the future and the present. Of course, this raises the core question of the evaluation of wealth and welfare for each generation, which requires a strong theoretical framework. It may explain why so many tools and models are weak in addressing intergenerational issues.

1.4. From local to global and vice versa

Climate change is one of the best examples of a global problem: climate change mitigation policies require a worldwide solution and worldwide agreement, and every country stands to benefit from them. Yet "global" does not necessarily mean “worldwide”: it means that, for a given stakeholder, the costs and benefits of a policy are not directly linked and dependent on his own actions (this is based on the externality concept). Over the long term, furthermore, the importance of the global dimension appears to be growing (externalities intervene both statically and dynamically). Sustainable development requires tackling both the global and local dimensions. This means that impacts and actions have to be evaluated at all levels, from the level of anonymous people (citizens, consumers, workers, politicians…) to that of governments and organised social, political, and economic institutions. This intertwining of the global and local perspectives is best expressed by a neologism: “glocality”.

Admittedly this may be, methodologically, the most challenging requirement. Although it cannot be equated with the micro-macro articulation problem, it comes pretty close to it. The micro-macro articulation problem is an as yet unresolved one in the social sciences (economics, geography, sociology) and, as Max-Neef argued, in development policies as well (Max-Neef, 1991). To our knowledge there have been very few experiences in hierarchical, multi-level model building. The “Second Report to the Club of Rome” (Mesarovic and Pestel, 1974) is an exception, still to be considered one of the most ambitious and impressive achievements in what remains a fundamentally top-down approach. The recent and rapid development of the multi-agent paradigm and evolutionary systems are promising in this respect.

1.5. Stakeholder participation

The participation of stakeholders is essential to sustainable development. It is closely related to good governance and democracy, and it becomes more crucial as the questions addressed become more global or uncertain. The role of stakeholders must be recognised and their viewpoints taken into account. Ideally, integration of the various stakeholders into the decision process should take place at each stage of the process. This means that the institutional setting in which decisions are to be made must provide for the participation of the various stakeholders from the very beginning to the end.

Stakeholders have a double role in decision-making. First, as “local experts”, possessing valuable information and knowledge about the system or the problem at stake. The methodological problem here is how to collect and formalise this knowledge and integrate it into the model. Standard survey methods and opinion polls are of course relevant here, but so are less conventional tools such as the *Delphi method*, *cognitive maps*, and various participatory methodologies.

Of course, there is more to stakeholder participation than just taking opinions into account. If a simulation model is used to support policy making, the stakeholders should be involved, as much as possible, in the modelling process itself, in defining scenarios and hypotheses, and in analysing the various runs. This means that the principles on which the methodology is based must be, by and large, understood and accepted by the stakeholders. Secondly, if stakeholders are to be involved in implementing the policy or if they simply must endure its - possibly adverse - effects, they should participate in the aggregation and selection stage of the decision process. This opens the way to a more systematic use of multi-criteria or multi-attribute decision tools and also collaborative decision-making methodologies (Paruccini *et al*., 1997), where a consensus over the objectives even has to be elaborated. Consensus-building conferences are an example of this approach.

In summary, stakeholder participation requires specific tools promoting collaboration towards defining objectives and evaluating effects, but it also requires making existing tools more accessible to “naïve” but concerned citizens.

1.6. Relationships between the criteria

It is crucial not to consider these five criteria separately. Take the "long-term perspective" criterion. As soon as we adopt a long-term perspective, we must also adopt an interdisciplinary approach, because the long-term perspective makes it necessary to look at how many different factors are evolving and are likely to evolve over the time span considered. This requires knowledge from many fields: demography (population trends), ecology (resilience of natural systems), economy (resource management), etc. The long-term criterion also makes it necessary to tackle uncertainty, as uncertainty becomes all the more important as the time span increases. Finally, the long-term criterion forces us to take into account the global dimension of the question considered. On the other hand, applying the long-term criterion does not absolutely require including the role of stakeholders, except as regards future generations, but these are already the core focus of the long-term criterion.

A more complete analysis of these relationships is proposed in a paper by Boulanger and Bréchet (2001).

2. Tools for decision-making

2.1. The distinction between tools and models

Decision-making is only one stage in the ongoing interaction between one or many actors and the system in which they are embedded and which they are trying to adapt to their own needs and wants by way of goal-oriented actions. The actions consist in modifying the spontaneous state or evolution of the system by way of addition (adding new elements such as dams, roads, power plants, institutions), subtraction (removing elements), or transformation.

In the context of sustainable development, decision-making is usually referred to as policy making, an interaction between political actors and the socio-environmental system they have to control in order to bring it to a state more desirable from a certain axiological perspective or to avoid spontaneous evolutions that are deemed harmful.

Formally, any decision problem can be represented by a decision table where each row is assigned to one element (a_i) of the set of possible actions to be considered by the decision maker, and each column to a possible state of nature (q_j), i.e. the outcome of all the external factors which are beyond the control of the decision-maker [2](q)(French, 1984).

At the crossing of row i and column j, one finds the consequences of action a_i provided one observes the state of nature q_j, say x_{ij}.

Table 1. Decision table: general form

States of nature					
Actions		q_1	q_2	…	q_n
	a_1	x_{11}	x_{12}	…	x_{1n}
	a_2	x_{21}	x_{22}		x_{2n}
	.	.	.	…	.

[2] In a strictly deterministic universe where only one state of nature could occur, there would be no need for several columns, one would suffice.

	.	.	.	…	.
	.	.	.	…	.
	a_m	X_{m1}	X_{m2}		X_{mn}

It is apparent from Table 1 that:

- the set of all possible actions has to be known and finite,

- the actions are mutually exclusive and only one must be chosen,

- the set of all possible (mutually exclusive) states of the world must be known,

- the consequences of each action for every possible state of nature must be known.

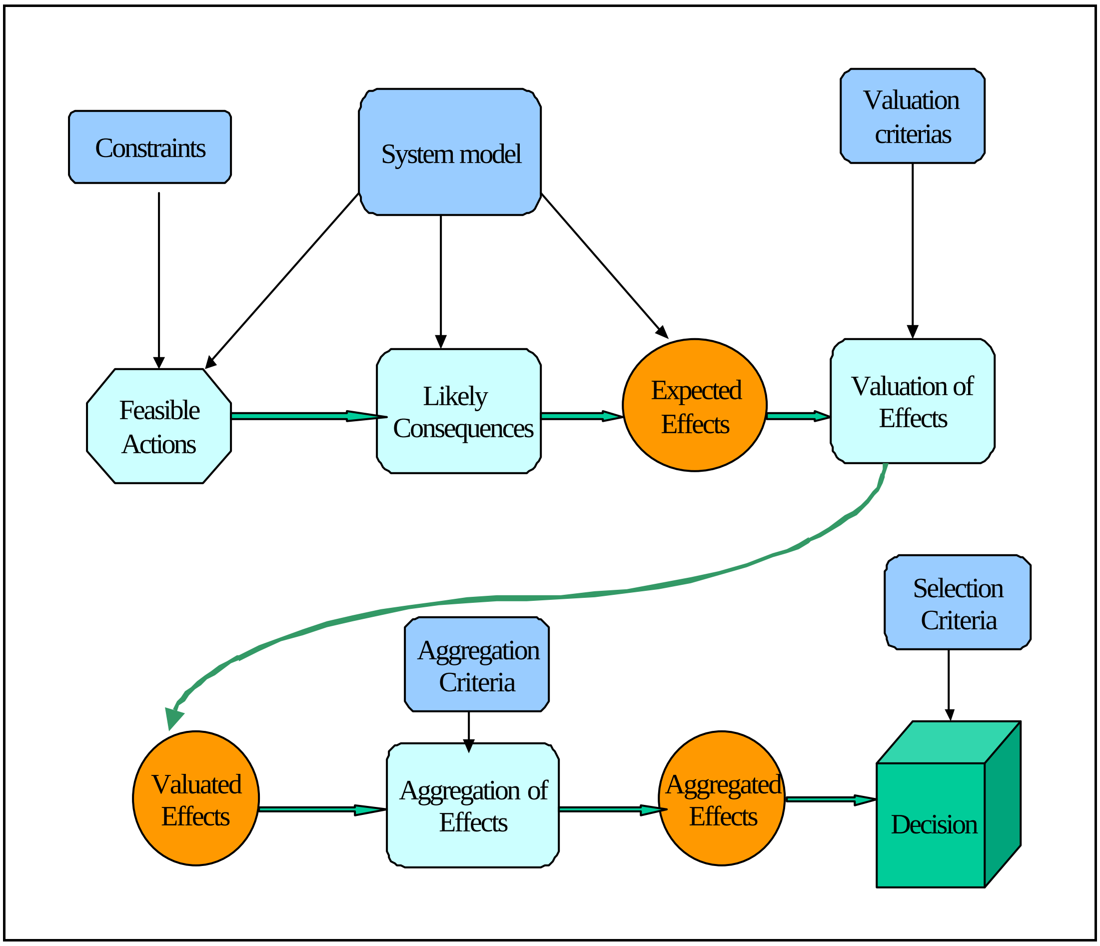
Once all these conditions are fulfilled, the decision problem boils down to:

1° *evaluating the alternatives:* this amounts to replacing each consequence in Table 1 with its value (“utility”) for the decision-maker;

2° *selecting the best alternative:* this simply means choosing the action leading to the highest-valued consequence.

Decision-making is thus best understood as a process consisting of identifying feasible actions, valuing and evaluating their likely consequences, then selecting the most appropriate sequence of actions, and finally, monitoring their effects and assessing their impacts. Depending on the outcome of the monitoring and assessment stage, in case of a discrepancy between the expected and observed consequences, the process can eventually be repeated. The process is displayed in Figure 1.

Figure 1 : The decision-making process (adapted from Walliser, 1977)



A rational or science-based decision-making process makes use of various scientific and technological tools at each stage, in order to:

- identify the most desirable state of the system with regard to the actors' goals and values,
- establish a list of feasible actions,
- assess their probable impact on the system (likely consequences and expected effects),

- evaluate their real cost,

- choose one of them, which may be tricky when there is a plurality of actors with conflicting interests or when there is no unanimous ranking of the feasible actions,

- monitor its real impact, etc.

Actually, decision-making involves at least two interacting systems:

- the decision-maker's own objectives, goals, values and constraints,

- the target system one wants to control, upon which one wants to act [3].

One may thus classify these tools in two broad categories: actor- oriented and system-oriented tools.

2.2. System-oriented tools

The first category consists of tools designed to help clarify the decision-maker's own constraints, goals, objectives, and preferences and to translate them into a language that allows their rational analysis. These tools also deal with valuation and ranking of expected consequences and selection of optimal actions. They mainly include methods such as cost-benefit, cost-effectiveness, or multi-criteria analysis, which are grounded in theories and models such as decision theory but cannot themselves be viewed as models.

The second category of tools helps to provide the decision-maker with the necessary information about the system, its evolution, how to interact with it, how to control it, etc. This is where *information systems* come into play.

Any information system is composed of:

[3] We are aware that in social and economic policy, the decision-maker is generally part of the target system. Yet it is also true that in order to control the system one must stand back and see oneself as being outside or above the system.

- a collection of data generally organised as a *database*. The database is an ordered collection of records about the target system and the decision-maker's resources. It is structured in the same way as the decision table. The most usual database system model - the *relational data model* (Date, 1986) - is designed as a table where columns refer to the attributes of the system and rows to the various entities composing it (in a cross-sectional approach) or to the same system across time (in a chronological approach). At the crossing of row *i* and column *j* one finds the value of attribute *i* for entity *j* or at time *j*. For instance, rows may refer to successive dates or to geographical entities such as cities or regions, and columns to variables such as GDP, population, CO_2 emissions, etc,

- *models* making use of these data for describing the system, simulating it, or predicting its future state(s). The role of models is crucial in science-based policy making. How could one design policies geared towards bringing a complex system onto a more desirable development path without at least having an informal mental representation of it and without making a distinction (however diffuse) between the system elements on which it is possible or most useful to act and other elements deemed less controllable or even uncontrollable? A model is any representation of a real system acting as a substitute for it and used in order to better know or control the system and forecast its evolution. In the case of policy-making, use is made of a specific class of models, namely control or technological models. These are mathematical (or logical) representations of systems which, contrary to pure-science or even applied-science models, focus mainly on the interaction between actors or decision-makers and the system to be controlled. This is why some authors like Bunge (1985) call them "technological models": even if they are truly science-based, their purpose is not knowledge per se but action and policy-making,

- a *user interface* by which decision-makers can interact with the database and model(s), enter their own data, hypotheses and scenarios, or visualise raw data, indicators, and model outputs. This is an important, yet often underestimated, component of any useful information system.

In technological models, one category of variables is of special relevance, namely *control variables*. These variables intervene in the representation of the target system but also belong to the set of policy instruments with which the policymaker is equipped. They stand, as it were, at the intersection between the system and the actor. The distinction between control variables and other variables (state variables, input and output variables) is what makes technological models different from scientific or theoretical models. The latter have no use of such a distinction, as their purpose is not to transform reality but to explain, predict, or analyse it. There are other important differences between pure scientific and technological models:

- Scientific models are more parsimonious than technological ones. Because technological models have to be more realistic than purely scientific ones, they are generally more complex, with many more variables and relations. Just think about the difference in scale between growth models and macro-econometric models in economics. The former may count no more than two or three equations, as opposed to hundreds in the latter case.

- Being more complex, technological models are often analytically intractable and can only be resolved by computational methods (simulations). This is why their development is so tightly associated with the development of the computer industry.

- As they include many variables, technological models are generally more demanding in terms of data, and they may use a broader set of data than just scientific facts or data. There is room here for what Funtowicz and Ravetz (1992) call “extended facts”: educated guesses, local knowledge, beliefs and feelings of stakeholders, testimonies, etc.

Since the Second World War, whole disciplines have been devoted to building and refining such models: operational research, cybernetics, optimal control theory, system analysis, system dynamics, and more.

Like control variables, *indicators* have a special status amongst the other components of the information system. It is by way of indicators that policy-makers become aware of a system’s malfunctioning, set quantitative targets for their policies, and monitor the effectiveness of their actions. As such, indicators also belong at the intersection between actor-oriented and target-system-oriented models.

2.3. Actor-oriented tools

Amongst the best-known tools on the actor’s side of the decision-making process are *cost-benefit analysis*, *cost-effectiveness analysis*, and *multi-criteria analysis*. They are used to evaluate alternatives by balancing costs and benefits (monetised insofar as possible) aggregated over different dimensions: time (which leads to the discounting problem), stakeholders (which leads to the aggregation problem), domains (which leads to the weighting problem).

If both costs and benefits can be monetised, cost-benefit analysis can be used. If only cost can be monetised, then cost-effectiveness analysis helps to choose the least costly way to achieve an objective that has been measured in non-monetary terms. Both of these tools rely on the possibility of summarising all the expected consequences of the decision in a single index, be it monetary (cost-benefit analysis) or not. When this is impossible, as is often the case with sustainable development issues, multi-criteria analysis is relevant.

The monetisation required for cost-benefit analysis is generally based on market prices, which are supposed to reveal consumer preferences. When no market price exists, as with many environmental services, amenities, etc, one has to resort to indirect methods such as *hedonic price methods* or *contingent valuation* methods, which involve asking people about their willingness to pay for a good or to accept compensation for its loss.

3. The main kinds of models used for decision-making

The most familiar models used for decision-making are the following: computable general equilibrium models, macro-econometric models, systemic models, multi-agent models. Each of these model types can be confronted with the criteria discussed above in order to check how they help us handle sustainable development issues.

3.1. Macro-econometric models

Macro-econometric models are said to have begun with Tinbergen in 1936: he presented the first example of a complete, specified, and validated macro-economic model. *Complete* means that the model covered the whole national economy; *specified* means that its behavioural equations are written in mathematical form; validated means that the model is applied to a database coming from national accounts and that the values of the coefficients and parameters are estimated by econometric methods. Artus *et al*. (1986) highlight two characteristic methodological features of Tinbergen's work. On the one hand, the model is designed to answer a concrete economic policy question: is it possible for a small, open, depressed economy to support its internal economic activity without damaging the external trade balance? On the other hand, Tinbergen pointed out a very fundamental feature of modelling: formalising a set of complex phenomena in a simple manner. The representation process (stylisation) calls for a judgment from the modeller on what is important and what is less crucial for the question addressed. To answer the question, the representation cannot remain merely qualitative but must reach a quantitative stage.

The use of econometric methods makes possible a crucial step: validation of these models. All behavioural equations are validated by econometric methods, and this means that they are able to reproduce the trends observed in past periods, with a given precision (goodness-to-fit statistics). No equation can be introduced into the model if it is not validated with data. So the model as a whole is able to fit the past evolution of the economy for the main macro-economic and sectoral variables (value added, employment, prices, investment...), and errors are not so important (*ex post* simulations reveal that errors come mainly from assumptions on exogenous variables).

The econometric nature of these models makes them well suited for short- or medium-term forecasts (less than ten years).

It is clear that, stemming from Tinbergen's approach, macroeconometric models are fundamentally designed to evaluate the macro-sectoral impacts of economic policies. They are used every day in the main administrations in charge of economic and sectoral policies. They allow two kinds of applications:

- short- and medium-term forecasts

- economic policy evaluations

In both cases, the public finance dimension is crucial and the models are used to evaluate the budgetary impacts of various scenarios. The results of the simulations make it possible to evaluate the room for budget policy in the forthcoming years. This entails that these models are often very detailed from a public finance standpoint. Typical fields of application are budgetary and fiscal policies in favour of employment, activity, investment, or the environment. These models can also evaluate impacts of a modification on exogenous variables such as raw material prices, external trade, exchange rates…

The strength of macro-econometric models relies on strong integration of the sectoral, macro-economic, and budgetary perspectives. The whole is validated by means of econometric methods. As a result, the field of exogenous variables remains limited (there are fewer exogenous variables than endogenous variables). The limitations of macro-econometric models stem both from their theoretical bases and from the use of econometrics. The models are characterised by neo-Keynesian mechanisms; this means that their dynamics is mainly driven by demand effects and that supply effects are strongly neglected or underestimated. The same holds true for the effects of R&D on productivity. Moreover, Lucas's critique concerning rational expectations, pinpointing a possible structural weakness, has not been answered convincingly. The argument is that econometric estimations are no longer valid once the behaviour of economic agents is influenced by economic policy. Sims (1980) points out another structural weakness: the problems linked to macro-level identification of structural models.

Since the work of Tinbergen and Klein, macro-econometric models have been widely used as tools for decision-making. They are used regularly in most developed countries, for both short- and medium-term macro-economic forecasting and policy evaluations.

Macroeconometric models have been extended to incorporate environmental dimensions, particularly energy. A good example of an operational model used intensively throughout the European Union is HERMES. Yet interdisciplinarity is rarely considered as such and the models are not extended or fundamentally altered in order to integrate issues connected with other scientific disciplines. In other words, most of the time, macroeconomic models are purely economic.

Uncertainty is estimated by sensitivity analysis, but the assessment is based mainly on assumptions, not on structural parameters or coefficients. The coefficients of behavioural equations are validated by econometrics, but the level of confidence is not taken into account when the whole model is simulated. Although these equations are stochastic, the simulations remain deterministic and the results are displayed without any level of confidence.

Concerning stakeholder participation, one must bear in mind that macro-econometric models are designed for public decision-making. The models distinguish agents insofar as they play a key role from a macro-policy standpoint: institutions (national banks, administrations, social security institutions), consumers, and firms. The administration in charge of the model can use it in a participatory process linked to public decision-making (assumptions and resultants may be discussed in Parliament or at any assembly of representatives). Finally, the global dimension is sometimes taken into account: there exist supra-national and worldwide macro-econometric models. *Glocality* is never considered as such since these models remain macro-models built on aggregated data.

3.2. Computable general equilibrium models

Computable general equilibrium models (CGE) rely on a Walrasian representation of the economy. They emphasise changes in relative prices considering a market equilibrium between supply and demand. Whereas macro-econometric models are driven by changes in aggregate quantities, CGE models focus on micro-optimisation behaviours of agents (consumers, firms, government…) and on the functioning of markets. The condition of general equilibrium (first formulated by Walras) states that there exists a vector of prices such that all the markets in the economy are at equilibrium. Micro-economic theory proves that this equilibrium allows an efficient allocation of resources. The algorithm of Scarf (1973) makes it possible to compute the general equilibrium and to evaluate the impacts of alternative fiscal policies on the allocation of resources (Shoven and Whalley, 1992).

Intrinsically, sectoral CGE models (like macro-econometric models) require an input-output table to model interrelations between productive sectors, but the determination of prices *via* equilibrium allows a perfect integration of nominal and real variables, which is not the case for macro-econometric models.

The critiques of Lucas and Sims are no longer valid here, as CGE models work on structural behaviours themselves, the macro results coming from an aggregation of the micro results. CGE models are based on microeconomic theory and benefit from its strong theoretical coherence.

Generally, the values of parameters and coefficients are calibrated and not estimated by econometrics. Calibration is a mathematical method for calculating the value of parameters, given the database for the reference year and the values of some coefficients obtained from the literature or from relevant econometric studies. This makes it possible to build CGE models even when the amount of available data is limited. The work of Jorgenson and Wilcoxen (1993) is a notable exception. Calibration opens the door to a more prospective modelling approach, since the model is not expected to reproduce past evolution. What is tested is the impact of alternative theoretical specifications on the functioning of the market and the allocation of resources in the context of policy making. Calibration requires a more systematic utilisation of sensitivity analysis, and this is a long tradition in CGE modelling. Sensitivity analysis procedures can be very complex (the tests can be either deterministic or stochastic). Unfortunately, this methodology is limited by the number of parameters: CGE models are often very disaggregated (hundreds of households or productive sectors can be distinguished) and the number of parameters is far too high for systematic sensitivity analysis.

CGE models can be static or dynamic. Because of their assumptions regarding perfect information and price flexibility, CGE models are generally seen as “long-term models”. Some models, however, include adjustment costs or imperfect competition. Others distinguish generations of agents (e.g. overlapping generations models). This opens the way to coping with intergenerational equity issues.

From all the features presented above, it clearly appears that the results of CGE models have to be considered indicative rather than realistic. CGE models are not forecasting models. Welfare impacts are calculated in the framework of welfare economics (and with reference to Pareto optima) since it is the best indicator of resource allocation within the economy. The objective of economic policy therefore consists in looking for alternative fiscal structures capable of improving economic efficiency as a whole, given the budget constraints of the economic agents.

Many CGE models have been developed in the last 20 years for handling economic and environmental issues (the European GEM-E3 model for example). The general equilibrium framework make it possible to evaluate the functioning of policy instruments such as tradable permits, for example. CGE models are also particularly helpful in addressing issues concerning international trade, global pollution…

The main advantages of CGE models stem from their strong theoretical microeconomic framework. Micro-economic behaviours are perfectly described from a structural point of view, which is not the case in macro-econometric models (see for example the Phillips curve used for the determination of wages). The main shortcomings of these models come from their Walrasian framework and its practical dimension – CGE models often bear little resemblance to reality and can be seen as "numerical implementations of theoretical models" (Fankhauser and McCoy, 1997). Practically, CGE models say nothing about adjustment paths, absolute price levels, growth dynamics... Insights from these models ought to be considered in relation to the theoretical framework. This complicates their interpretation.

Interdisciplinarity is not a strong point of CGE models, because of the strong economic foundations required. The main extensions are to energy, pollution, and distribution issues. Some modellers (e.g. Bergman) have adapted the welfare function to take into account the quality of the environment, but the approach cannot be seen as an integrated assessment (see below the discussion on Integrated Assessment Models). Concerning uncertainty, it has been explained how sensitivity analyses are applied and their limits. The fact that, in some circumstances, very few data are necessary to build a CGE model is in favour of their use for international issues or in developing countries.

3.3. System theory and systems models

Sustainable development literature abounds in references to a system approach or to a systemic standpoint, but what this means, exactly, is not always very clear (Svedin 2001). The expression "system approach" may mean something quite different according to the author or scientific discipline. For some, it means a general conceptual framework; for others, it means very specific methodologies (system dynamics, for instance) or even computer programs such as Stella© or Vensim©.

However different these definitions, all references to a systemic standpoint share a common background, which can be summarised as follows:

- whatever their ontological substance (physical, biological, social, cultural), things are best understood as organised complexities (systems) composed of more elementary elements maintaining structured relationships (structure),

- these systems are embedded in environments (themselves composed of other systems) with which they exchange matter, energy and information,

- the behaviour of a system results from the interplay between its internal structure and interactions with its environment.

A system can thus be characterised by its composition (elements composing it), its structure (nature of relations between the components), and its environment.

From the start (say, the publication of Von Bertalanffy's "General System theory" - GST, for short- in 1968), system theory has claimed to be an interdisciplinary, or we should say now a transdisciplinary theory:

> "Entities of an essentially new sort are entering the sphere of scientific thought. Classical science in its diverse disciplines, be it chemistry, biology, psychology or the social sciences, tried to isolate the elements of the observed universe – chemical compounds and enzymes, cells, elementary sensations, freely competing individuals, what not – expecting that putting them together again, conceptually and experimentally, the whole or system – cell, mind, society – would result and be intelligible. Now we have learned that for an understanding not only the elements but their interrelations as well are required: say, the interplay of enzymes in a cell, of many mental processes conscious and unconscious, the structure and dynamics of social systems and the like. This requires explorations of the many systems in our observed universe in their own right and specificities. Furthermore, it turns out that there are aspects, correspondences and isomorphisms common to 'systems'. This is the domain of *general system theory*."[4]

Cross-fertilisation between the emerging technological discipline of control theory or cybernetics and the new general system theory has led to characterising a system's structure in terms of positive or negative feedback loops, responsible for the often counter-intuitive and non-linear behaviour of complex systems. Formalisation of these feedback loops as integro-differential equations has led to mathematical models of systems and to their analysis in terms of state space, phase space, attractors, chaos, etc.

System dynamics is one of the most successful offshoots of GST. It is the adaptation (with simplification), by Jay Forrester, of the main concepts and mathematical formalisms of GST to management and policy science. Its success is largely due to graphical tools and user-friendly computer software that make it much easier for non-mathematically inclined people to build, analyse, and simulate system models.

System dynamics played an important role in the emergence of the sustainable development concept, Forrester's World Dynamics and Meadows's World 3 ("Limits to Growth") being direct applications of it.

One of the main difficulties in building system dynamics models has to do with the huge amount of data necessary for their identification and estimation. Even when these data are available, parameter estimation remains a difficult exercise when

[4] Von Bertalanffy (1971), Preface to the British edition, p.xvii-xviii.

relationships between variables exhibit a high level of non-linearity. This is a problem, because system dynamics models may be very sensitive to initial conditions.

System dynamics models are generally standalone, but they can be associated with other model types. This is the case of CELSS (Coastal Ecological Landscape Spatial Simulation), a cellular automata model consisting of 2,479 interconnected cells simulating a coastal territory, each cell being modelled as a dynamic system (Maxwell and Constanza, 1994).

With respect to the five attributes sustainable development models should ideally exhibit, system models, and specifically system dynamics models, fare rather well.

- System theory is a truly transdisciplinary language, sufficient for enabling communication between different disciplines and as a frame for interdisciplinary topics. The question is rather: which disciplines? These must be developed enough to be amenable to mathematical formalisation in terms of differential or difference equations.

- System models can tackle the long-term problem. One can also easily build very disaggregated embedded generation models with simulation software such as Vensim or Stella. It may be more difficult to intertwine different time scales inside the same model.

- System dynamics models are inherently deterministic. Of course, it is always possible to check the robustness of results to slight variations in parameters or initial values, but one must admit that sensitivity analysis, though relatively easy to do, is too rarely undertaken.

- Thanks to some cheap and user-friendly simulation software, it is quite easy to interact with system dynamics models: changing parameter values, initial conditions, scenario hypotheses, and even the very relationships between variables is attainable by non-specialists, as is visualisation of the system's behaviour through time by way of graphical displays. Since the very beginning, proponents of system dynamics methodology have emphasised the importance of involving the “client” in the model building and analysis process.

- The most famous (if not necessarily the best) system dynamics models applied to sustainable development are worldwide models. They have been rightly criticised for being much to aggregated. Conceptually, nothing prevents the construction of more disaggregated models, as proposed in Mesarovic and Pestel’s Second Report to the Club of Rome.

3.4. From system theory to multi-agent models

One of the main shortcomings of system dynamics models lies in the immutability of their structure. The model cannot evolve or transform during simulation runs.

The only things that can change during runs are the values of the variables, not the nature of the relationships between them. No scenario, even the most imaginative, could bring about the emergence of new relationship patterns or new entities. The same holds for the border between the system and its environment. It is given once and for all and is not susceptible to any change whatsoever.

It is very difficult in such a framework to reproduce an evolution, adaptation, or development involving a new definition of the borderline between a system and its environment or the creation of new subsystems, for example, by diversification, complexification, specialisation, etc.

The new-generation system theory, called “complex system theory” (Holland, 1998), tries to overcome these limitations. Multi-agent models belong to this new generation of complex system models.

These models mainly simulate (by way of computer programs) whole populations of autonomous agents interacting with each other inside an artificial environment. The latter is generally reduced to a very abstract structure of elementary cells (lattice, torus) equipped with a limited set of dynamic properties (stocks of resources, absorption capacity for a pollutant, etc.), but nothing prevents a modeller from representing more realistically real territories with their geological, ecological, or social properties.

Agents are more or less autonomous entities, generally aware of their environment (i.e., the inner state of the cell on which they stand) and of their own needs, able to move from one cell to another, to feed themselves, to cooperate, compete, to fight with others, to self-reproduce, and eventually, to die. They can also act upon their environment and modify it.

Each agent is embodied in a program that dictates its behaviour on the basis of certain objectives (to survive, to accumulate, to reproduce itself…), its internal state, and its environment.

Multi-agent models are inherently stochastic: conclusions are drawn from the analysis of multiple simulation runs with randomised initial conditions and parameter values.

Very often, the underlying theoretical paradigm is evolutionist ("Darwin in silicon"), the model reproducing the "struggle for life" of different populations (equipped with different behavioural repertoires or cognitive skills) in the same environment. The population best adapted to the environment will exhibit a higher survival rate and reproductive success and become more and more numerous as time goes by, contrary to the least adapted one, which will eventually disappear. It is thus possible to detect which behavioural repertoire or social arrangement gives the best survival probability to a population of agents in a given environment. Of course, the simulation may also consist in studying the survival chances of the same population under varying environmental conditions.

Thus, if sustainability is defined as the long-lasting adaptation of a species to a specific environment, there is no doubt that multi-agent modelling must be a privileged way to study it. In what remains the most stimulating example of multi-agent modelling (or artificial society, as it is sometimes called) Epstein and Axtell (1996) propose a very operational definition of unsustainability:

"In this context, when people are saying that some behaviour – a rule – is 'unsustainable', they mean that continued operation under the relevant behavioural rule will transform the environment – perhaps quite suddenly and irreversibly – into one that is highly inhospitable to agents obeying that rule" (p. 163).

Multi-agent models have a lot to offer in the area of sustainable development assessment for the following reasons:

- They make it relatively easy to organise cooperation between scientific disciplines. Natural scientists and ecologists may endow the artificial environment with whatever property they want and populate it with whatever species they find relevant, while social scientists may simulate various behavioural patterns or institutional arrangements. Even a whole cultural system can be reproduced with its specific patterns of perception, its communication channels, norms, values etc.

- This approach is fundamentally bottom-up. Higher-level structures and systems can be analysed as emerging from the interactions of (sometimes very simple) local rules or behaviours. In turn, these higher-level structures, once created, influence lower-level interactions. It is then possible to simulate multi-level systems and interactions between the global and the local levels.

- Multi-agent or artificial society models of very ancient societies (as in the "Evolution of Organised Societies" project) or collapsed civilisations ("Artificial Anasazi") have been elaborated, demonstrating that the approach is well suited to the long, and even very long term (15,000 years for the EOS project).

4. Integrated assessment and sustainability impact assessment

Integrated assessment (IA) and sustainability impact assessment (SIA) are relative newcomers to the scientific community. Their novelty and originality reside in the fact that they do not aim to propose new kinds of tools but rather to develop more efficient ways to make existing tools collaborate in the decision-making process, notably (for SIA) in a sustainable development context. Of course, this means dealing with interdisciplinarity, uncertainties, stakeholder involvement, etc. So the present discussion might be said to belong to the IA and SIA fields.

Integrated Assessment is a practice combining different strands of knowledge in order to accurately represent and analyse real-world problems of interest to decision-makers (Rotmans and van Asselt, 2001). It is a rapidly developing field of research involving scientists from several disciplines and decision-makers. Many illustrations of it are available in the literature concerning environmental issues such as acid rain (Hordijk and Kroeze, 1997) or climate change (Morgan and Dowlatabadi, 1996).

The IPCC gives the following definition for IA: “assessment is integrated when it draws on a broader set of knowledge domains than are represented in the research product of a single discipline. Assessment is distinguished from disciplinary research by its purpose: to inform policy and decision making rather than to advance knowledge for its intrinsic value”.

Rotmans and Dowlatabadi specify this definition as follows (quoted by Hisschemöller *et al*): “in general, IA assessment can be defined as an interdisciplinary process of combining, interpreting and communicating knowledge from diverse scientific disciplines in such a way that the whole cause-effect chain of a problem can be evaluated from a synoptic perspective with two characteristics:

- IAs should have added value compared to single oriented assessment,

- IAs should provide useful information to decision-makers.

IA explicitly deals with two of our criteria, namely interdisciplinarity and uncertainty. A plurality of approaches is required, ranging from model-based methods to participatory methods. This shows that IA has to be considered as a framework for organising and structuring various pieces of recent scientific tools and insights. Moreover, a key issue in the IA approach is how to handle uncertainties coming from the very imperfection of scientific knowledge in the disciplines considered (Rotmans and van Asselt, 2001). It follows that IA has to deal with a great variety of sources of uncertainty and tries to structure and combine them within a comprehensive cause-effect chain.

IA is often carried out with models (IAMs). These models explicitly encompass scientific theory and data in a precise and computable way. As IA combines different disciplines, IAMs consist of coupled mono-disciplinary modules. each discipline-specific component can be used alone or linked to the other modules through the exchange of data, either by a soft-link (the modules are not necessarily in the same computing environment) or by a hard-link (a common shell). The latter is preferable in theory or simply to ensure overall coherence, but sometimes it is simply impossible to achieve. There can be many reasons for this, such as: different time paths to be considered, different modelling concepts in use (simulation *versus* optimisation), data of different quality (nature, availability, aggregation…).

The use of IAMs must be linked to the decision process (see Rotmans and van Asselt, 2001). From this perspective, IAMs can be considered a cornerstone of Sustainability Impact Assessment (SIA).

Methodologies for analyzing separately economic, social or environmental dimensions are very common. Good examples include cost-benefit analysis, environmental assessment, and macroeconomic modelling. Most researchers agree that more than a single methodology is required to address macroeconomic and sectoral issues, household- or firm-level impacts, or environmental management, essentially because each of these topics raises stakeholder-specific questions. SIA methodology consists in:

- an evaluation of the impacts associated with all policy measures in the different fields involved (economic, social, and environmental impacts) and all relationships and feedback effects,

- a description, both qualitative and quantitative or monetary, of each impact,

- a definition of losers and winners among the stakeholders.

Clearly, SIA is a method rather than a tool as defined above. It can use different tools for different purposes. For example, one way to present and handle the impacts is to use multi-criteria analysis, one way to evaluate sectoral impacts is to use an input-output framework, one way to take into account the functioning of the markets is to use general equilibrium models, one way to deal with stakeholders is participation and consultation, and so on…

To understand SIA it is necessary to pay special attention to all relevant impacts and their feedbacks. This general framework provides added value in the sense that it applies to a single set of issues and goals a combination of interrelated tools or models. The aim is to go beyond the insights given separately by each tool or model so as to encompass all the insights in a general policy and scientific debate. Introducing the criteria discussed at the beginning of this presentation into the SIA framework depends merely on their being introduced into each tool and model used. SIA allows strong integration of criteria such as participation or uncertainty within the overall method. This is encouraged by the use of different kinds of tools from different scientific fields.

Conclusion

In the field of sustainable development, there is a growing consensus amongst scientists in all disciplines regarding the need to take into account the five criteria discussed here. This consensus has paved the way to entirely new disciplines (or new names for old practices?) such as Integrated Assessment and Sustainable Impact Assessment. Will this be enough?

It is certainly a good thing to have specialists in interdisciplinarity, risk analysis, etc., but we also need more integration of interdisciplinarity, glocality, and so on into traditional disciplines. Thus, the next step is to analyse in greater depth the epistemological and methodological implications of integrating these criteria into the common practice of the various disciplines involved in sustainable development.

There are preliminary questions we must strive to answer, such as: when is interdisciplinarity fully achieved? Can it be achieved without questioning the fundamental paradigms of each scientific discipline? Can it be handled without explicit mathematical modelling? Does its practice make it necessary to adopt a common transdisciplinary language such as system theory?

Similar questions should be asked about the other criteria. For example, what are the conditions of successful integration of stakeholders? Have we examples of genuine multi-level analysis for decision-making?

In summary, we need benchmarks and best practices in these matters. One way to begin defining them would be to collect success stories and failure cases in sustainable development research, and to analyse them in order to determine what makes the difference between success and failure.

Obviously, of the various modelling methodologies outlined in this paper, some look more promising than others with respect to sustainable development requirements. Not surprisingly, the closer a methodology is to a particular science or discipline-specific paradigm, as in the case of macroeconometric or computable general equilibrium models, the less room it leaves for interdisciplinarity. Conversely, less specific methodologies such as system theory or multi-agent modelling are much more comfortable with this criterion. It would be interesting to see if, say a CGE model, could be translated into a system model or multi-agent model. If so, such practices should be fostered.

It is worth stressing that multi-agent modelling is still a very new method, almost in infancy. We think it should receive special attention from R&D decision-makers and funding agencies in order to help it reach its full potential as soon as possible.

Finally, we wish to advocate encouraging the scientific analysis of the decision-making process itself in a sustainable development context, in order to help design governance principles for dealing with long-term, transversal, social and environmental problems in a democratic way. Even the best information that science can provide would be totally useless without political institutions apt to make use of it.

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