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CONCEPTS AND MODEL IMPLICATIONS

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ECOLOGICALLY SUSTAINABLE ECONOMIC DEVELOPMENT: CONCEPTS AND MODEL IMPLICATIONS.*

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Abstract.

In this paper the implications of ecologically sustainable economic development for modeling are considered. First we discuss the concept of ecologically sustainable economic development and suggest that any description of it should consider four central concepts: intergenerational trade-off, interregional aspects, multiple use of resources, and risk and uncertainty. We discuss each of these at a conceptual level and consider the implications for model building and model use at both theoretical and operational levels. It is concluded that, although different approaches are possible, to a large extent similar requirements for models are to be fulfilled.

1. Introduction.

This paper aims at clarifying the concept of sustainable development from a modeling viewpoint and suggesting central components of it. These components will each be discussed separately, with specific emphasis on the design and use of models for sustainable development.

The concept of sustainable development is - particularly since the publication of the Brundtland report (WCED, 1987) - increasingly gaining popularity in integrated economic-ecological policy analysis and research. This concept reflects a compromise between growth advocates and ecologists. It recognizes the goal of survival of the human species, realization of an acceptable quality of life for each individual in present and future generations, preservation of diversity and quality in the natural environment, and wise management of natural resources and ecosystems.

In order to harmonize the actions of individuals striving for their own goals, in most countries an institutional system of regulations - rights and rules - is coming into being in order to prevent society from turning into an anarchy with unacceptable environmental externalities. No comprehensive regulation via a system of rights and rules exists that is satisfactory for real-world allocation and tuning. The current set of regulations in most countries may have some effect, but is mainly suited to correct for a socially undesired allocation over space or within the same generation. Although attention towards environmental problems is rising, the main concern of decisionmakers is still more about static than about dynamic distributional effects of developments. In a dynamic world we are not only facing static allocational and distributional problems, but also intricate problems of allocation of endowments - of any kind - over time.

This allocation over time results from the development within the ecological-economic system. The development of each sub-system has to be viewed in accordance with that of the other one. In conventional economics and ecology each system is usually studied separately from the other one, while both systems are assumed to behave independently of each other. No feedback of one system to the other is generally assumed. Usually one is interested in feasible and optimal time paths for the system as a whole, so that interactions and feedback mechanisms between the sub-systems may matter. One approach is taken to consider what the effects of a certain economic development are on developments in the ecological system. Starting from the ecological system, one can search for constraints that should be imposed on economic development paths to fulfill goals of conservation of ecosystems and sustainable yield of renewable resources.

'Sustainable' is a general concept which denotes that the necessary conditions for some phenomenon to take place are permanently satisfied. Therefore the following definition of ecologically sustainable economic development can be posed: the development of economic activities, human preferences and human population, such that an acceptable standard of life for every human being is fulfilled (the phenomenon) and all aspects of this development can be sustained in the long run by natural resource availability, ecosystems and life support systems (the necessary conditions).

'Ecologically sustainable' refers to the continued existence of the environment, which acts as a basis for human welfare as it provides living conditions and environmental amenities, and acts also as a productive basis.

The concept of 'acceptable standard of living' calls also for further explanation. Brown et al. (1987) state that all humans should, once born, live to adulthood with a quality of life beyond mere biological survival. Tolba (1987) mentions elements that are essential in arriving at such a quality: food self-reliance, health control, clean water and shelter. While these are especially relevant to developing countries, Pearce et al. (1988) mention additional attributes that are more relevant to developed countries: real income per capita, education, access to resources, basic freedom and distribution of income. And still more aspects may be relevant: price stability and regional balance.

The natural environment is in our definition classified as resource availability, ecosystems and life support systems. The latter are essential in providing living conditions for the human species. Resources generate flows of materials and services for economic activities. Ecosystems create conditions for economic activities and provide environmental amenities that make a direct contribution to the level of welfare.

Several elements in a sustainable development strategy can be distinguished, referring to non-renewable and renewable resources and pollution levels. Sustainable use is an element that may serve as a starting point to sustainable development. It refers in a narrow sense to renewable resources, in which case it means that the rate of harvesting or extraction of the resource is not higher than the controlled or natural regeneration rate. In a broader sense sustainable use may include also that pollution generation (waste, congestion) is kept below critical levels. These critical levels are determined on the basis of the assimilative capacity of ecosystems. Another element in sustainable development can be the sparingly use of scarce non-renewable resources. Also substitution and extinction are in principle allowed for in sustainable development. Substitution may occur between natural resources used in production or in generating environmental amenities. Also substitution between economic activities is an option, leading to qualitative changes in the economic system. Furthermore, technological innovation may lead to less intensive use of certain resources or to a replacement by others. Or it may induce the substitution of existing activities by new ones, leading also to qualitative changes in the economic system. Of course some ecosystems should be conserved as they provide living conditions or are crucial to the continued existence of larger natural systems.

These elements in a strategy for sustainable development - a global concept - offer meaningful starting points for operationalizing sustainable development at a meso level of aggregation. A meso level is useful for implementing sustainable development for the following reasons: interactions and feedback mechanisms are easier tracable than at a global level; environmental decisionmaking can easier be guided by a regional governmental agency; regions have specific problems or capacities that should be dealt with in their right context and level of detail. Thus the implementation of sustainable development at an operational level calls for a specific choice of a spatial scale. A regional scale of analysis for a finite number of generations is relevant, attainable and apt for accuracy. Furthermore, the time scale is also important. In general, the time horizon may be determined on the basis of uncertainty and regeneration rates of renewable natural resources involved.

In the following section sustainable development will be placed in a three-dimensional context of time, space and substance so that a distinction of important components can be made. Next, in section 3 these dimensions will be discussed at a lower level of abstraction along with implications for modeling for sustainable development.

2. Dimensions of Ecologically Sustainable Development.

Now we will place sustainable development in a three dimensional context of time, space and 'substance', in order to get a clear view on the many aspects related to it.

Time can be measured on a continuous or discrete (equidistant) scale. The largest time horizon is still finite, but may be approximated by an infinite horizon. Three types of time can be distinguished, viz. sequential, computational and cumulative time. The first one refers to the fact that events and decisions have consequences and are thus extended over time.

The second type of time is connected with both computational algorithms and adjustment processes, and hence with the common feature of stability. The third category concerns the transfer of embodied information with the passage of time, either through activities by man or by way of an autonomous process, or by a combination of both.

The dimension space can be subdivided into geographical parts each having the capacity and place for containing some unique entity that is either useful or necessary to discern it from its surroundings. This means that two such parts, which are different in terms of place, will not generally be of the same shape. The sum of all these parts is clearly finite in every direction (e.g., a region and the atmosphere).

'Substance' refers to basic units of a system and may include inter alia potential energy, a living entity, or a system (an individual, a population, an ecosystem, an economy or economic sector, a region, etc). A possible distinction of 'substance' is into human actors, non-human actors (living organisms) and the non-living physical environment. The latter class is dominated by processes in space and time of an autonomous intrinsic physical nature, and is influenced by the first two groups (i.e., human and non-human actors). The second class changes in an evolutionary way along a path guided by laws of the system of living organisms and sometimes disturbed by physical events and often by human intervention. The class of human actors evolves strongly both in terms of number and influence on both other classes hence, making itself increasingly dependent on these. The space characteristics of a certain 'substance' do perhaps not differ much among some individuals (e.g. individuals in a population), but they may do so in other cases (e.g. industries, forests, rivers, populations, sub-regions in a region). The time characteristics can be very different, for instance, different 'substances' may take part in processes with different flow velocities (some processes are measured in eons, others in microseconds, just to name some extremes).

In economic models man plays a role in different ways. First, human decisionmaking at a micro level can be described by relating individual behavioural characteristics to external data and developments. Often the actors decisions interfere with one another, like for example in the use of a common property resource (e.g., fishery, or soil, air and water in the case of pollution), and sometimes it may be necessary to control for the outcomes of such interactive processes by directing actions through certain policy instruments such that socially determined goals will be realized. This second way of human action is at a different level than the first one and can be described as an optimization of some social objective, while of course taking into consideration the behaviour of individuals as well as economic and ecological processes and interactions.

In the sequel we will discuss four central components of sustainable development, viz. intergenerational aspects, interregional trade-off, multiple use, and uncertainty and risk. Although more components can be distinguished than we do here, the most important ones will be mentioned here. However, it is very difficult to formulate components that are entirely non-overlapping in terms of elements of sustainability.

The sequential aspect of time and the central role of man as indicated are also reflected in the intergenerational aspects of sustainability. The problem that arises in this specific context is that of intergenerational equity (or welfare distribution). The question of how to compare the distribution of welfare over time has been the subject of much debate in economics and has resulted in several viewpoints regarding the specification of a social objective function and in many different opinions concerning discount rates to be used in some realistic setting, for example in energy policy (Lind 1982). Also from a theoretical and practical angle various other problems arise, viz. regarding the measurement and comparability of utility that individuals attach to a given social state.

Both computational and cumulative time are related to uncertainty. The computational aspect refers to stability of equilibria of processes. Dependent on the strength of the stability forces pulling the state of the system back to equilibrium, the system in an equilibrium state may exhibit a certain degree of uncertainty without leaving its equilibrium neighbourhood. In this respect also the question arises how much time it takes to close gaps between present and desired (or equilibrium) values of variables. Since we opted for both a limited space horizon, leading to a distinction into regions, interactions between regions and the trade-off between equity and efficiency should be considered. These problems and arguments for specific choices of a regional subdivision will be treated hereafter under the heading of interregional trade-offs.

The discussion following the introduction of 'substance' denotes the fact that most entities use and are used by other entities for their existence. It is not an exception that one entity makes use of several others, possibly at the same time (e.g., a factory using water for cleaning or cooling purposes and using air, water or soil for discharge of its residuals). Here, an entity may denote bounded organisations ranging from (non-)human individuals and populations to eco-systems and economic systems. It is also possible that an entity provides several services to one or more other entities. The latter is known as multiple use.

Ecologically sustainable economic development should be preceded by the identification of a time path of economic activities that takes account of constraints on the possible time paths of ecosystems elements, such that the state of the entire interacting economic-ecological system - represented by appropriate states of all elements in both sub-systems - follows a time path that satisfies the optimal balancing of relevant indicators or criteria within given contraints. The optimal balancing follows from the evaluation of the social (intergenerational) objective function for each feasible time path of the systems variables. In a more operational sense this can be performed in a multiobjective framework or by using satisficing levels for relevant indicator variables.

3. Components of Sustainable Development and Model Implications.

In the present section we will discuss in more detail the central components of sustainable development that were indicated in the previous section.

3.1. Intergenerational Trade-off.

Intergenerational elements include the time horizon, the social welfare function and bequest function, the social rate of discount and relevant restrictions/constraints. Restrictions can be classified as referring to stocks, controls, stock changes and integrals.

The time-horizon in a sustainability analysis is in general long, including the life span of at least two generations, in order to include intergenerational aspects. Uncertainty elements will make an infinite horizon unrealistic to work with. In sustainable development, long-term behaviour - trends and structural changes - are important. Stability issues at both the economic and ecological systems level may then be relevant for outcomes in the long run. Unfortunately, short-term adjustment processes - concerned with departures from equilibrium - and long-term trends - assuming equilibrium - and structural change are often not compatible in a modeling framework. Models are either fitted to short-term data and are only adequate for describing short-term processes, or only long-term data are used and most accurately generated (see Ayres 1978). In an operational context, a choice of the time horizon depends also on the dynamic behaviour of renewable resources that are important to the region considered.

A social welfare function serves as an evaluation criterion for the identification of decisions. In an ideal situation this evaluation would be based on a social welfare ranking of all possible social states. Here we regard a social state in a general way, viz. the distribution of all goods, services and other utility-determining factors, information, and nature in all its aspects ("quality" and "quantity") over time, space and individuals. A social ranking can be arrived at by aggregating individual welfare rankings of social states. In a static context that would imply a choice for a welfare function with as arguments the utilities of all individual members of a generation at a certain point in time. In a dynamic sense, a social welfare function is based on the utilities of all individuals over time. An individual's welfare ranking is usually made explicit by introducing utility functions. For aggregation of rankings it is necessary to assume - in addition to the usual ordinal significance measurability feature -that cardinal significant individual utility functions be constructed. We make here the distinction between comparability of individual ranking in one generation and that in different generations. For both purposes the cardinal significance condition on utility functions is necessary, whilst for intergenerational comparability also the choice of a discount factor has to be considered.

As a result of the above mentioned aggregation procedure we assume the existence of a social welfare function, through which a ranking of alternative social states is possible. One possible choice of such an aggregate welfare function that is justified by different moral systems (viz., Classical Utilitarianism and the Intuist conceptions; Dasgupta and Heal 1979), is the additive, separable utility function, that can be formulated (respectively for discrete and continuous time dimensions) as:

$$(1) \qquad \sum_{i=0}^{L_0} u_0^i + \sum_{t=1}^{T} [[1/\prod_{s=1}^{t}(1+\delta_s)^s] \sum_{i=1}^{L_t} [u_t^i(x)]]$$

and

$$(2) \qquad \int_0^T \exp\{-\int_0^t \delta_s \, ds\} \sum_{i=1}^{L_t} u_t^i(x) \, dt \, .$$

Here it is assumed that the discount rate δ_t, the number of individuals in the generation at time t (period t) L_t, and the utility function of individual i $u_t^i(\,)$ may change over time. All relevant information on social states is incorporated in x(t) (denoted by x). The time horizon T is regarded as finite. If in the continuous case the time horizon (which might artificially be seen as the time of extinction of the human race on earth) is following a distribution with a probability density function p(T), then (2) may be generalized as:

$$(3) \qquad \int_0^{\infty}\int_0^{T} \exp\{-\int_0^{t}\delta_s ds\} \sum_{i=1}^{L_t} u_t^{i}(x)p(T)\, dtdT .$$

If T is large, an infinite value may be used without making a significant error. On the other hand, if T is infinite, the total infinite sum (1) (or integral (2)) may be replaced by a finite one with a bequest function and additional conditions on stock variables. The lump sum term should approximate the expected total discounted utility to T of social states from time T onwards. This approach bears much resemblance to the way decisions are made in reality, as in general no planner is able to work with infinite horizons.

An alternative welfare criteria is the maximin criterion based on the ethical ideas of Rawls (1971). The objective function to be maximized in this case is

$$(4) \qquad \min_{t \in [0,t]} [C(t)].$$

This criterion takes the intergenerational equity most strongly into account, because it concentrates only on the welfare of the generation that is worst off. Thus substitution between generations' utilities will not be stimulated by this social welfare fuction, in sofar as it does not make the inequality in the distribution of utility of generations over time smaller. This is a contrast with the utilitarian criterion by which it may be optimal - in terms of the total welfare weighted by a discount factor - that one generation is subjected to bad circumstances in order to make life for succeeding generations better. The underlying idea for the latter is thus that a certain decrease in welfare for one generation can be compensated by an increase for another. The fulfilment of such a program implies for a society starting with poverty that it will endure poverty over all succeeding generations. This problem cannot be satisfactorily overcome with an intergenerationally extended 'max-min' principle, for example one in which the utility of one generation is made dependent on both its own consumption level and that of the next generation (Dasgupta, 1974). Then (9) is replaced by

$$(5) \qquad \min_{i \in N} U[C(i),C(i+1)],$$

where i denotes the place of a generation in the total sequence of generations, and

$N = \{1,2,...,n\}$, with n the total number of generations living in [0,T]. Even with a further extension of care for future generations, a permanent escape from the initial level of consumption or capital assets is not possible (see Dasgupta 1974). The initial consumption level is free in the model, i.e. it will be determined as part of the optimal solution. Alternatively an initial consumption level can be added to the model - as in the case of an initial stock value - resulting from past developments. Imposing a sustainable development constraint - requiring that the consumption level may not decrease - will ensure then even more rigidity than the minmax criterion already does.

A bequest function can be added to the welfare criterion in our model for the finite horizon problem, in terms of the utility of the terminal capital stock. This reflects the expected total discounted utility to T of social states from time T onwards, given the stock level at T. A bequest function can be seen as a more flexible generalization of a finite stock restriction. Other stocks than the capital goods stock can be valued at the date T. Especially in the context of the problems stated in later sections, stocks of pollution and resources may be considered appropriate. They both are important for the welfare that can be attained by generations living after T.

A next intergenerational element is discounting. This cannot be seen separately from the specification of the social welfare function, choice of time horizon and incorporation of risk in the model model. Discounting has to originate from the measure of time preference, which can be made explicit through awarding certain shadow prices to reserving present consumption/production possibilities for future opportunities. A possible way of adjusting a valuation is by correcting costs and benefits upward or downward. Alternatively, costs an benefits with possibly varying social rates of time preference may be used (see Gijsbers and Nijkamp 1988). However varying rates over different investment projects may cause the problem of financial crowding out. Also a explicit consideration of the relation between the social rate of discount and opportunity costs is useful (see Pearce and Nash 1981). In general the social rate of discount value should at least be as high as the opportunity cost rate. In a second-best world they will in general not be equal to the social time preference rate. Of course it is then important to set boundaries in order to avoid that all technically possible investments are regarded as realistic feasible opportunities. For the assesment of opportunity costs one needs to determine the welfare forgone by not having endowments available for immediate consumption or reinvestment. So opportunities include those for the present as well as the future. Representation of opportunity costs is possible by means of shadow prices of capital. If these can be assessed, they may be used to transform costs and benefits of investments into private sector equivalents. In this way the issues of social rate of time preference and opportunity cost can be separately dealt with in a modelling sense. Finally, it is would also be possible to include a premium (positive or negative) for risk.

It is sometimes argued that it is preferable to undertake a 'pure' discounting by using only the social rate of time preference, while all other aspects mentioned above (including possibly also externalities and intangible elements) can be incorporated in other ways. If discounting is purely based on the social rate of time preference, then the question of identifying the optimal rate emerges. A simple solution to this problem is choosing the social rate equal to the market rate of interest. Many discussions can be found in the literature on these topics of efficient allocation of investment funds, varying discount rates, and differing discount rates between social and private investments (see also Lind 1982, and Nijkamp and Rouwendal 1988). Finally we add that a reduction in the value of the discount rate may induce the same actions or conclusions as a positive savings rate of resource use.

A major advantage of incorporating many aspects under the heading of one discount factor is that it adds to the simplicity of the model structure. Clearly, clarity and simplicity, which in this respect seem to be contrary, are to be traded off against each other here.

Ethical objections against positive discount rates have been expressed from various angles (see for some of them Opschoor 1987). Also it may be argued that, although individuals use positive discount and time preference rates, this situation does not necessarily carry over to a community or generation. However, the risk argument still holds for communities and may imply a positive social rate of discount.

In addition to the functional form of the objective function and the problem of discounting, also the incorporation of intergenerational aspects in state transition equations including initial and final conditions on states has to be mentioned. First, when using dynamic equations (e.g., difference equations), the unit of time is important. If one unit corresponds to the time-span of a human generation, clearly the dynamic system is not flexible enough to describe smooth adjustment processes. Of course different processes in reality have different dynamics and feedback loops, which means that actually the distinction of variables into stocks and flows is somewhat artificial. In such cases essentially different flow rates should be used.

Intergenerational aspects can be taken into account by including conditions on initial and final values of state variables in a model. If T for instance is finite, then a condition for acceptable state values at time T can provide a guarantee that generations living after time T have the endowments and abilities to satisfy their needs to an acceptable standard. Every generation can - on the basis of a moving forward procedure - optimize (2) for some finite time. The conditions on the starting states would then be determined by the preceding generation, while the end-conditions would be set by the present generation and serve as starting conditions on states for the next generation. In this way the optimizing problem with an infinite time horizon can stepwise be approximated by means of a combination of sub-problems with a finite horizon, which are inter-related by the initial and end state conditions of the respective dynamic equations.

Another way of capturing inter-generational aspects is putting side-conditions on control variables and changes in stock values. For example, consider a renewable resource that is used for economic purposes. Suppose that its dynamic behaviour can be described by the following equation:

$$(4)\quad \dot{y} = F(y) - h(t),$$

in which $y(t) = y$ denotes the total biomass (or population size, or - in case of a non-living resource - another measure of quantity or quality). Now $\delta y/\delta t = \dot{y}$ is the net change in bio-mass, resulting from natural growth according to the rate F( ) and from harvesting with a capture rate h(t) the resource is subject to. The well-known notion of sustainable use of a renewable resource in this case would hold if the side condition $\dot{y} = 0$ would be satisfied all the time. Theoretically this is an idea easy to cope with, but for some specific resources no guarantee of y taking on specific values can easily be given. Instead an inequality condition is much easier to impose, because safety margins may then be accounted for. These can make up for the fact that the exact determination of the precise dynamic behaviour of a renewable resource and exact information about stock levels is very difficult. Also the uncertain influences on dynamics add to this unprecision; this aspect will be dealt with later on in the next issue of sustainable development, viz. risk and uncertainty. An example of a safety inequality in the renewable resource example above may be to impose the condition $\dot{y} \geq \epsilon > 0$ or:

$$(5)\quad h(t) \leq F(y) - \epsilon$$

A problem may here arise in pursuing such a strategy, as the stock may increase and a possible profit may be lost (maybe to other - natural - predators). However, in case of a closed loop (feedback) control, this poses no real difficulty, because the harvesting

institution can observe the growth of the resource and react to it in an appropriate way. In reality such closed loop controls are however not always possible (e.g., in fishery).
Also one may use as an indicator the ratio of rates of change in the stock (or depletion/growth rate) to the stock level. This may then indicate the variability or time of complete depletion (if present rates of depletion are continued) of the stock.

Finally, meaningful conditions may also be included from imposing upper or lower bounds on integrals. First, the objective might be changed from maximizing an integral function (functional) to the restriction that the same integral function will not attain a value below/above a critical boundary value. Secondly, irrespective of the objective form, an integral restriction may be added to the problem that ensures that for instance income or derived consumption (in money or utility terms) received during some period exceeds some minimum necessary level, sufficient resources of some kind are available over a given period (i.e., the period over which the integration takes place), or no more than a maximum amount of pollution is emitted during a given period.

In conclusion, intergenerational issues can be dealt with in a modeling framework in many ways. Some of the approaches are overlapping in terms of description or effect, and therefore a combination of complementary approaches in this sense should be aimed for in model building for sustainable development.

3.2. Interregional Trade-off.

In many cases we lack sufficient insight into the working of natural and economic processes. When also the mutual relationships between these two processes are considered, much adittional uncertainty and many complications are introduced. This provides a definite reason for choosing specific natural systems for observation or analysis, especially when their existence seems crucial to human well-being (directly or through economic production activities). For the same reason one may analyse the behaviour of specific economic activities in relation to those parts of the natural environment upon which they act and depend most strongly. Other reasons for setting geographical boundaries on systems under consideration are of a more practical nature, and are related to data and precision of description, the existence of administrative/institutional regimes for regions, etc.

In the context of a discussion on sustainable development, it is noteworthy that in general sustainable development refers to fairly large spatial units (e.g., continents, countries). The spatial demarcation of an area from the viewpoint of sustainable development is far from easy, as a compromise has to be found between functional economic and ecological areas. The choice will be co-determined by data availability: if economic data at different levels are abundant, it seems plausible to let the regional demarcation be determined by ecological coherence, and vice versa. In any case, in view of the need for operational policies a meso level of analysis which is also in agreement with administrative possibilities is desirable.

If one aims at modelling an integrated regional economic-ecological system, the first choice concerns the specific regional boundaries. It is related to the objective of the study that the model-builders or regional planners have in mind. It may be based on purely economic grounds, for example, when an analysis is pursued to determine the effects of certain economic activities on the natural environment. It might also originate from the physical or natural system that constitutes the basis of regional activities. In that case the borders of the resources or ecosystems are crucial (which can range for instance from a forest or a river to groundwater). If a region is based solely on either economic or ecological arguments its size may be such that important relationships in the other system cannot be included appropriately in the regional model (see Brouwer 1987). To combine the two one may try to minimize all kinds of material and money flows, either economic-demographic or physical-ecological. Clearly, for a smaller region the need to model interregional flows is in general larger.

If one assumes, for modelling purposes, that key variables from outside the region, impacting on variables inside the region, are given (and hence no feedback influence is possible), then one region may be modelled separately, conditional on certain external parameters. If more regions are involved in this way we obtain a so-called top-down approach. These are a member of the family of regional-national (or multiregional) models, in which it is assumed that supply and demand are cleared at the national level, so that linkages between regions do not have to be modelled explicitly (see Issaev et al. 1982).

Next, interregional linkages, both economic and ecological have to be considered. Economic-demographic interactions are especially important when transportation costs and mobility of resources are substantial. The flows between regions (e.g., goods, services, money, production factors, people, information, pollutants, groundwater, surface-water, nutrients, animals, etc.) are different in many respects, e.g., in terms of measurement units, rates, travel distances, variation over time, etc. Other characteristic of flows refer to their control (is control possible, and if so, how) and changes in their structure or composition (e.g., pollution transfer involving chemical transformations); some flows are difficult to follow over time (for instance, chemical flows), or pass through living and nonliving nature (e.g., nutrient flows). Another distinction is between purely economic, purely ecological and mixed flows, to be defined as moving only in the economic or ecological system or moving between both systems, respectively.

A problem that arises when some regional utility measure is maximized (e.g., regional welfare) is that of spatial spill-overs. For instance, from a national point of view the shadow prices of e.g. pollution do not rightly reflect scarcity. This will lead in different regions to over-use or under-use of goods and services in production and consumption, and consequently an undesired distribution of pollution. A solution may be obtained by putting national constraints on the behaviour of regional authorities, or by allowing for bargaining between regions (implying problems to be solved through game-theoretic approaches).

In order to deal with the spatial equity problem, one may either set a minimum level for the total regional derived utility by using appropriate indicators (e.g., income per capita, unemployment, public services, pollution, congestion, noise, m2 vegetation and parks per capita).

The combination of sustainable development and the regional scale provides some ideas for the design of models. A national-(multi)regional integrated model provides the right tool for operationalizing the above concepts.

3.3. Multiple Use.

The fact that individuals, populations, natural resources, or parts of (or whole) ecosystems may perform different tasks (or have several functions), provides the possibility for economic actors to use them in several ways at the same time. When such activities do not interfere in both economic and ecological respects, they can be considered independently from each other. The use levels of certain resources that optimize benefits for each activity can then be determined separately and are in combination also optimal from the viewpoint of total benefit. Often however, activities do interfere, e.g. when they are competitive or when problems of project evaluation have to be solved in order to reach political agreement. Besides, one activity may have a (complementary) positive effect on another one, (e.g. when it generates cash-flows that fit in the investment schedule of the other one).

Problems of the latter type are all dealt with in the field of capital budgetting (see for an overview Copeland and Weston 1983).

In general, ecosystems, populations and resources may provide services for both natural and economic activities. An example, which has been the subject of many modelling activities, is a species functioning both as a prey for a natural and a human predator (e.g., the fishery sector). In this case the services provided to the different users are of the same nature. Another example is the well-known problem of the open-access fishery or common-property use of some area or ecosystem. But the services may also be very different, like a forest that provides timber, recreational facilities, a stable flora and fauna, regulation of precipitation and evaporation of water, assimilation, diminishing pollutant levels, etc.

In using or affecting a resource base, economic activities and natural processes may be independent, competitive (in several degrees, like the extreme case of exclusiveness), complementary or commutative. Some of the relations may be one-sided, e.g., when one activity/process influences the possibilities of another activity/process. If a relationship is two-sided or inter-active, it may be symmetric (e.g., in the case of two predator species preying on the same prey species and in common-property use), or it may be asymmetrical (e.g., in a predator-prey relationship).

The modelling of inter-active relations for multiple use situations in the form of mathematical equations will result in dynamic systems, consisting of difference or differential equations, which have usually non-linear behavioural characteristics. This may imply that the structure of the model in terms of its behaviour may change drastically when certain parameters of the model exceed critical values (e.g., when the number and/or place of stable points changes). Bifurcation and chaos theory studies such properties of dynamic systems (see Kelsey 1988). A dynamic system that does not have this property is called structurally stable. While such indirect non-linearities may occur even with single equations in the system having a linear form, synergetic effects of variables influencing the dynamic behaviour of a certain variable will have to be modelled by a (direct) non-linear dynamic equation. Moreover, a non-linear equation may also be needed as it may more adequately describe the effect of one variable on the dynamic behaviour. As the behaviour of non-linear systems can lead to surprises, it is necessary to take care in acting upon them in one or another way. As in most cases the continued existence of such a system will be one of the elements in a sustainable development strategy, study of the characteristics is especially for such strange behaving systems relevant.

When one considers the multiple use of natural systems and resources, one aims at determining the optimal combination of activities and their respective levels of intensity, which determines the respective use levels and together the total effect on the system or resource in use. One way to model this is optimizing the total benefit from all considered activities taking into account the dynamics imposed by all activity levels and the constraints arising from both interferences of activities at the economic and ecological level. We will use as an illustration the following model.

Suppose two species, whose biomasses are denoted by respectively x and y, are competing for the same food. If both species can be harvested, then let h(t) and g(t) be the respective rates of harvest at time t, and resulting benefits with rates denoted by B1(h(t)) and B2(g(t)). Assume that the amount of capital necessary for both harvesting activities is identical. This capital is denoted by K1(h(t)) and K2(g(t)), and constrained by total available capital, denoted by K(t) with price ck(t). Capital is assumed to depreciate at a rate proportional to the stock of capital which can be increased through investments. If an investor, expecting a budget flow W(t), wants to determine the flows of investment and harvest rates such that total discounted benefits over a period with horizon T are optimized, then he should solve the next problem:

$$\max_{I,h,g} \int_0^T \exp\{-\delta t\}\left(B1(h(t)) + B2(g(t)) - ck(t)I(t) \right)dt$$

s.t. $\dot{x} = rx(1-x/k)-\alpha xy-h(t)$,

$\dot{y} = sy(1-y/l)-\beta xy-g(t)$,

$\dot{K} = I(t)- dK(t)$,

$0 \leq I(t) \leq W(t)$,

$K1(h(t)) + K2(g(t)) \leq K(t)$,

$h(t), g(t) \geq 0$ and

$K(0)=K_0,\ x(0)=x_0,\ y(0)=y_0$.

For the species dynamics we have used here Gause's model of inter-species competition (see Clark 1976). Multiple use refers here to the entire ecological system, modelled here for the two species case and its environment. The feedback of a change in the environment (e.g., the amount of food or the concentration of animals) to the population changes in both species - as a result of a change in the species levels - is implicitly incorporated in the model via the parameters r,k,s and l. This model brings together features that are separately treated in Clark et al. (1979) and Bishop and Samples (1980).

Another approach to dealing with multiple use is to let the allocation of funds to different activities or the destination of a resource to various uses be determined through multiobjective programming. Each activity may add an objective. If a specific use of the resource is essential, a constraint on the remaining use can be formulated.

Multiple use of a resource can lead to many relationships between the resource and economic activities, as a result of which a complex model may result. If moreover non-linear equations are included in the description of multiple use of the resource, solving a kind of optimal combination of use will be difficult or impossible. Sustainable development may include multiple use of a resource, such that all uses follow stable patterns, and the resource-base remains intact. Simulation exercises can provide indications about the right combination of multiple uses regarding stable development of the resource-base and the uses.

Analysing the concept of multiple use offers some ideas for modeling. However, optimizing for multiple use situations may lead to difficult problems, while even determination of multiple use that fits in a sustainable development strategy can be difficult.

3.4. Risk and Uncertainty.

3.4.1. Prologue.

In a technical sense one can distinguish between certainty, risk, uncertainty in a strict sense, and surprise. In case of certainty all events caused by other events and human actions are supposed to be completely sure and known. In case of risk, the existence of an event is known, but its occurrence is not certain; however, one can assign a probability to each possible event (or a probability density function to all possible events when they follow a continuous pattern). With uncertainty the possible events are known, but no indication on the probability distribution of their occurrences exists. Finally, a surprise denotes an event that was not expected ex ante with any reasonable insight.

Although quantum field theory (in physics) has indicated the unpredictable character of micro-level dynamics in particles, it is not the main cause for uncertainty regarding the behaviour of economic-ecological systems. One cause from which uncertainty arises is the insufficient knowledge about the relationships, interactions between variables in the economic-ecological system, especially concerning processes such as changing preferences and development of knowledge and techniques. Another cause pertains to the errors in a model that result from the inability to take all relevant relationships into consideration, as well as from inaccurate or insufficient data. For instance, a frequently used model to describe population dynamics of species is the logistic growth curve in differential form:

$$\dot{b} = rb(1-b/k),$$

where b denotes the population biomass or number of individuals. This is a so-called lumped parameter model in which no distinction is made between parameters determining net biological growth. For instance the parameter k, often denoted by the term carrying capacity, contains many aspects of the environment which become scarce if the population keeps growing in number and which have thus an adverse effect on population. This model does not accurately describe the dynamics of a real-world population, because too many factors and dynamic processes are left out. This means that we will at best be able to get an impression on how a population may evolve, but the precise outcome will be uncertain. Deciding whether or not to choose such a model often comes down to weighting the accuracy of its descriptions and the tractability of time-paths generated by it. To handle more efficiently incoming information, and thus decreasing uncertainty, one may choose to use models that use step-wise new information. For instance, Bayesian updating uses risks measures that change as information becomes available.

In the context of sustainability it is clear that much risk and uncertainty emerges from structural changes in a system, which are not due to stochastic changes but to integral shifts in behavioural patterns, exogenous impacts or changes in policy institutions. Thus in such cases sustainability cannot be defined as an optimal system's trajectory with a given (stochastic) parameter space, but as a set of sequential optimality regimes governed by sometimes dissipative structures.

In the following sections we will consider the way economic theory has dealt with uncertainty and discuss the implications for models to be used for sustainable development issues.

3.4.2. Economics Aspects of Uncertainty.

Risk and uncertainty are conventional topics in decision theory. Approaches to risk analysis are state-preference theory (focussing on the allocation of resources under uncertainty) and (statistical-)parameter-preference approaches (focussing on the allocation of risks). The latter approach has provided the basis for important developments in the theory of finance (e.g., C.A.P.M.; see Copeland and Weston 1983). Central in the first approach is the concept of contingent consumption claims: goods are defined to have - in addition to the normal features (physical and service attributes, location, date) - also a subscription to states of nature (states of the world). For such goods a special preference theory has been developed: expected utility theory (see von Neumann and Morgenstern 1944).

Two forms of uncertainty are normally dealt with, viz. market uncertainty and technological (event) uncertainty (see Hirshleifer and Riley 1979). In the first concept individuals are uncertain about the actions of other economic agents. At the micro-economic level, search processes dominate, while at a macro/meso level market disequilibrium and price dynamics are essential. This form of uncertainty concerns the endogenous variables of the economic system and is intitutionally induced. Event uncertainty on the other hand deals with exogenous data, viz. resource endowments and production possibilities. In the case of exhaustible resources, it is linked with e.g. size and quality of resource reserves, costs of extraction, discovery of new reserves and invention of substitute products .

Decision-makers can take either terminal actions or informational actions. The first actions (passive) will allow individuals to adapt to uncertainty, while by means of the second (active) one individuals can overcome uncertainty. Within the class of terminal actions, we can distinguish between the trade, sharing or modification of risk. Informational decision-making starts with the acquisition of an information service followed by Bayesian updating of subjective prior probabilities assigned to states of the world (for statistical decision theory see DeGroot 1970). Besides, information may also emerge autonomously with the mere passage of time. Then a trade-off between costs of waiting and irreversibility of some development is possible.

Values of informational activities are based upon the expected utility gains from shifting to better choices among the set of terminal actions. A special informational activity relevant to sustainable development is an indirect one, viz. waiting, in order to benefit from the so-called option value (or flexibility value) (see Fisher and Krutilla 1985). This option value is defined as the gain from being able to learn about future benefits, that would be precluded by some development, if one does not initially develop (preservation). Thus, option value is a conditional value of information and exceeds (or equals) the unconditional value of information.

3.4.3. Inclusion of uncertainty in modeling.

For a choice of tools to be used for implementing risk into analyses, there is a large body of techniques, models and rules.
Techniques as sensitivity analysis and probability analysis (low probability/high impact analysis; Monte-Carlo experiments), or decision theoretic models (e.g., statistical sequential decision models).

Also several practical approaches to the treatment of risk in benefit-cost analysis may be pursued: use risk-free rates of discount and adjust benefits and costs for risk; use risk-free rates and perform sensitivity analysis; for public investments with returns uncorrelated or negatively correlated with the total returns of a set of assets in a portfolio, the strategy can be discounting at the risk-free rate and taking in consideration the fact that the result understates the present value of the project.

Other rules of thumb may be used, like limiting the period of analysis and restricting the space dimensions of the problem under consideration. Comparison of expected values of benefits and costs is possible, or first reducing these with a premium because of risk-aversion of individuals.

Incorporating risk structures in models can be done appropriately in simulation experiments. When probability density functions can be specified, Monte-Carlo experiments are easy to perform. However, in case of long-term structural changes such experiments may be more difficult to undertake. Surprises can be dealt with by assuming all kinds of improbable developments in scenarios for simulations and investigating the effects on the time paths of indicator variables. Analysis of surprises is more in harmony with the search for sustainable development paths under uncertain conditions and may be based e.g. on forum or expert techniques (e.g., Delphi-methods).

In order to arrive at stronger (i.e., mathematically based) results, other model forms are available. Stochastic dynamic optimal control techniques are suitable, when a change in values of stock variables over time can be described by a process which has a drift and a diffusion component. The major shortcoming in such advanced techniques is the fact that the existence of an optimal solution requires specific mathematical features of functions used in the model. Moreover in case of a stochastic control problem with more than one state variable moving according to a stochastic process (or with restrictions on state and/or control variables), the determination of an optimal solution for the control variables is in general very difficult an in most cases impossible.

Alternatively, deterministic optimal control solutions may be derived, while the impact of disturbances in the paths of state variables on the value of the objective function can be investigated by means of simulation modelling. It makes much difference whether or not the optimal control path is very sensitive to slight disturbances in the paths of state variables. It is also important to know the character of stationary points and the sensitivity of equilibria. If more equilibria for the dynamic behaviour of the system output exist, it is necessary to know how the system can move from one to another equilibrium and what this implies for the value of the objective function. Also important is the study of the combined effect upon the system's behaviour and performance when multiple states behave in an uncertain way. For example, one can look into the effects of variables reaching very extreme values (in every possible direction) at the same time or for longer periods.

Of course, sensitivity analysis with respect to initial and end conditions on state variables, parameter values in objectives, state transition equations and constraints are meaningful when uncertainty on their specific values exists.

When the time horizon is very long, a control may be used to reach as fast as possible stationary values for the state variables and keeps them at those levels thereafter. These stationary values should be determined as the optimal solutions of a transformed problem, viz. the original objective subject to the variables satisfying static equivalents of the dynamic equations during the planning horizon. Moreover, it is then possible to add more constraints on state and control variables. In this way the solution to the original problem is approximated by steering the state as fast as possible to the stationary state, which is the solution to an equivalent static problem. Further refinements in this simple algorithm can lead to improvements. First, especially when dealing with uncertain behaviour of state variables, one has to consider the probabilities of moving away from an equilibrium, the character of the equilibrium and the effect on the performance criterion of a state moving away from an equilibrium.

It is noteworthy that in many cases optimal control models take for granted a fixed structure. This may be at odds with long-term changes in parameter structures, so that in that case a blend between optimal control theory and catastrophe theory (or chaos theory; see Kelsey, 1988) has to be used. Alternatively, several iterative linearizing parameter-improving optimization-approximation methods, with either closed loop or open loop control structures, can be found in the literature. Stochastic simulation with a nonlinear model and reestimation of a linear model while iteratively finding better controls is an approach to incorporating uncertainty. In these cases the parameters may change over time so as to allow for making small and drastic changes come out in the model strucure. The advantage of feedback control structures, necessary for control of stochastic systems, is the fact that the system behaviour under a given (and possibly optimal) control structure can be studied easily - for both deterministic and stochastic systems - (see Chow 1975).

4. Conclusions.

Modeling integrated ecological-economic systems for sustainable development has to be preceded by a thorough reflection on the concepts to be used. In this paper we have tried to treat this in a systematic manner. Important conclusions reached are: models should describe economic and ecological processes in sufficient and balanced detail; a starting point for the model building process may be either the economic activities module or the ecological basis for activities; all relevant information that is available and accessible should be taken in consideration in this framework; especially regional models are suitable for a detailed description of spatially varying but nevertheless interwoven phenomena; due attention should be paid to intergenerational aspects, interregional aspects, multiple use and uncertainties; the level of detail of the description and the structure of the model should be such that the model (or derived simplified models) can be analysed either analytically or with reliable numerical methods. It is clear that the idea of sustainable development needs further clarification and refinement in a specific empirical context. In addition to a systems-analytic meaning, it has also a policy-analytic meaning. In this regard, models pertaining to sustainable development problems should also incorporate risk strategies for policy actors.

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