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**OPERATIONALIZING SUSTAINABLE DEVELOPMENT:
DYNAMIC ECONOMIC-ECOLOGICAL MODELS.***

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Abstract.

Since the mid-eighties, a vast literature has evolved around the concept of sustainable development. It shows a wide support for changes in policy-making and decision-making, for instance, to integrate environmental interests in national and international political processes. Remarkably, recommendations of contours and new elements of research methods and policy analysis for sustainable development are rare, although this is just as essential as the renewed attention for the political dimension. A clear view on how to use and change adequately existing techniques and models for sustainable development will contribute to a more satisfactory operationalization of it.

This paper examines the implications of ecologically sustainable economic development for integrated dynamic modelling. After a concise discussion of sustainable development it is suggested that five concepts are central to it: intergenerational equity, the regional scale, multiple use, long term uncertainty, and economic-ecological integration. The discussion of each of these issues is focused on the implications for model elements and uses. Thereby, old ideas are reviewed and new ones are proposed. The aim is not to come up with a rigid framework for dealing with sustainable development but rather to suggest which alternatives are available to deal with the central concepts, although in a section on economic-ecological integration general requirements for dynamic economic-ecological models are mentioned explicitly in order to offer a general frame of reference. These requirements are fairly general and may be taken up in ensuing discussions of the methodological aspects related to sustainable development. The main conclusions are the following. We view economic-ecological integration in the sense of combining processes instead of one process and a variable. To deal with intergenerational equity one may choose objectives, various constraints, or a combination of both. For regional models one may consider various types of conditions on cross-boundary flows and external factors of regional processes. Multiple use can be modelled as an intermediate stage between single resource models with a partial view and complex models with a general view. Sensitivity, probability and scenario analyses can be used to deal partially with the various types of long term uncertainty, although this remains

difficult for the very important class of unexpected events or catastrophes. Such surprises can at best be turned into risk by scenario analyses and examination of dynamic behaviour of the system as a whole.

1. Introduction.

The notion of sustainable development calls for drastic changes in our current modes of production, consumption and decision-making. In the Bergen Conference on 'Sustainable Development, Science and Policy' (NAVF, 1990) also the role of science (and science policy) in stimulating sustainable development is emphasized, as it has become evident that our scientific apparatus is far from adequate in this context. Thus there is a clear need for a re-orientation of our analytical thinking.

This paper aims at clarifying the concept of sustainable development from a modelling viewpoint. Central components are suggested and each of these will be discussed separately, with specific emphasis on the design and use of models for analyzing sustainable development.

The concept of sustainable development is - particularly since the publication of the Brundtland report (WCED, 1987) - increasingly gaining popularity, not only in policy platforms but also in integrated economic-ecological research and policy analysis¹. Questions like climate change, global acidification, deforestation or ozone depletion are increasingly looked at from the viewpoint of sustainable development. The use of the notion of sustainable development can be regarded as the result of a need to solve a potential or actual conflict between growth and conservation, with a particular view on efficiency and equity, now and in the future. It recognizes the goal of survival of the human species, of the realization of an acceptable quality of life for each individual in present and future generations, of the preservation of diversity and quality in the natural environment, and of a wise management of natural resources and ecosystems (cf. Barbier 1989; Redclift 1987).

Although in many countries an institutional system of regulations exists for decreasing negative environmental externalities, it is unsatisfactory for allocation and tuning in a pro-

¹ See for instance Redclift 1987; Repetto 1986; Tolba 1987; Pearce et al. 1989 and Simonis 1990 for literature with a strong bias towards developing countries. For a variety of other approaches see Hueting 1982; Opschoor 1987; Barbier 1989; Collard et al. 1988; Pearce 1988; Turner 1988; Pezzey 1989; De Vries 1989; and Archibugi and Nijkamp 1989. Some approaches that, in different ways, integrate economics and ecology are Hotelling 1978; Daly 1980; and Clark and Munn 1986.

active sense. The current set of rights and rules mainly serves to correct for socially undesired allocations of environmental externalities or transformations over space or within the same generation. Although the attention for environmental issues is rising, the main interest of decisionmakers lies still more in short term issues (or surprise-free megatrends) than in bifurcations or structural transformations generating unexpected dynamic distributional effects of developments (see Clark 1986).

Space-time distributional issues result from the evolution of ecological-economic systems, in which the development of each sub-system has to be viewed in relation to that of the other one. In conventional economics and ecology each such system is usually studied separately from the other one, while both systems are assumed to behave independently from each other. No feedback between these systems is generally assumed (e.g., in terms of resilience, carrying capacity or flexibility). From a societal viewpoint, however, one is usually interested in feasible and optimal time paths for the system as a whole, so that interactions and feedback mechanisms between the sub-systems do matter. A partial approach is then to consider the effects of a certain economic development on the ecological system. Or, starting from the ecological system, one may search for constraints to be imposed on economic development paths so that relevant goals are fulfilled like conservation of ecosystems and sustainable yield of renewable resources. It is evident that the issue of sustainable development will have major implications for modelling such dynamic systems.

'Sustainable development' 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 is proposed here: the dynamics in economic activities, human attitudes and human population, such that an acceptable standard of living for every human being is fulfilled (the phenomenon) and all aspects of this development can be ensured in the long run by the availability of natural resources, ecosystems and life support systems (the necessary conditions). The long run horizon leads to the need for monitoring evolutionary processes. For instance, climatic change which is projected to occur globally in the next decades may exhibit large interannual variations so

that a careful statistical interpretation is necessary.

The more limited concept of 'ecologically sustainable development' 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 (cf. Christensen 1989). For instance, the use of persistent micro-pollutants may in the short run increase agricultural productivity, while it may erode the ecological basis of agriculture in the long run. The natural environment also includes resources, which generate flows of materials for economic activities.

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 additional attributes - some of them more relevant to developed countries - can be mentioned: real income per capita, education, access to resources, basic freedom, distribution of income, price stability, regional balance, social welfare support, clean air, low congestion levels, sufficient living space, natural areas for recreation, etc..

In a sustainable development strategy the following elements can be distinguished². Keywords in that respect are sustainable use, sparing use, substitution and compensation. Sustainable use applies to the extraction of renewable resources, and it means that the rate of extraction of the resource is not higher than the controlled or natural regeneration rate. In a broader sense sustainable use may also imply that pollution generation (waste, congestion) is kept below critical levels. These critical levels are determined on the basis of the assimilative capacity of ecosystems.

² The elements focussed on here are on the action side, as this seems a logical step to implementation. On the effect side, one may for sustainable development require that natural patterns of geobiochemical flows are not changed beyond fluctuation ranges, that material flows are circular (closed), and that the diversity of species and ecosystems is preserved. They imply which actions should not be taken. In this paper we are more concerned with actions that should be taken.

For non-renewable resources sparing use may be stimulated, especially for the most scarce resources. Similarly, such a strategy may hold for renewable resources. Recycling and improvements in technology are essential in this respect.

Next, substitution of renewable for non-renewable resources may be enhanced. This may involve only substitution of inputs, or also substitution between production techniques and final products. So, it may lead to qualitative changes in the supply and demand side of economies.

Compensation is based on the idea that it is not necessary to preserve every single natural resource. It can take different forms. First, it may be based on keeping the total amount of man-made and natural resources constant (in terms of physical or value terms), so that economic capital may replace natural capital. However, as opposed to man-made capital, natural resources fulfil often multiple functions (both ecological and economic) while some of them are irreplaceable by man-made capital. Second, compensation may be interpreted as maintaining a constant level of natural resources, so that an increase in renewable resources must compensate for a decrease in non-renewable resources, and for resource degradation resulting from extraction, pollution and disruption. Intergenerational compensation projects should compensate negative impacts of the main project by performing (executing or financing) one or more secondary or 'shadow' projects such that the sum of the individual project damages is zero. This can be regarded as an alternative - and improvement - to the valuation of environmental damage and monetary compensation. Such projects aim to correct, diminish or compensate the dynamic physical impacts of the project, while the cost of the alternate project(s) allow(s) for corrections upon the cost-benefit analysis of the original project. 'Shadow' projects may either replace lost environmental values or avoid the environmental degradation and disturbance caused by the original project, where the last option is favoured (see Klaassen and Botterweg, 1976). The difficulties related to the idea of compensation are that natural resources fulfil many functions, and that future consequences of compensation projects may be many, uncertain, and also negative.

2. Dimensions of ecologically sustainable development.

In this section five issues are discussed which we regard as central to sustainable development. These are intergenerational equity, inter-regional links and trade-off, multiple use, long term uncertainty, and economic-ecological integration. We will suggest model requirements implied by each of them. The time dimension has links to continuity, long term existence and future generations. Basic to sustainable development is the idea that we have a responsibility for the well being of generations that will exist in the future. The problem that arises in this specific context is that of intergenerational equity. 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 social welfare functions, discounting and discount rates. In addition, we will discuss the use of intergenerational constraints on stocks, flows and integrals.

The element of time is also present in forces related to stability of equilibria of processes and the emergence of new information. Associated with sustainable development is the issue of long term uncertainty. Especially chaotic behaviour and surprises are interesting in that respect.

In view of the limited scope for operational guidelines in a global system, the regional scale of sustainable development should be considered. Thereby attention should be given to openness, cross-boundary flows, external factors and interregional trade-off. The use of (multi-)regional models for sustainable development is therefore needed.

Many natural systems and resources are used by several other entities, simultaneously or sequentially. Sometimes these uses are conflicting or complementary. A multiple use problem can be formulated that has to take into account both economic and natural functions provided.

The final important element in a discussion on sustainable development is that of integration of economics and ecology. Methodological differences between these disciplines may provide obstacles for integrating them. However, formal models may offer opportunities to combine many of their concepts, theories and conclusions. The next sections treat these

five issues in more detail in order to come up with suggestions for incorporating them in models.

3. Model implications of intergenerational considerations.

Elements of models that can incorporate intergenerational considerations are the time horizon, the social welfare function and bequest function, the social rate of discount and relevant constraints, classified as referring to stocks, controls, stock changes and integrals.

3.1. The time horizon and intergenerational welfare comparisons.

The time-horizon in a sustainable development analysis is in general long, covering a life span of at least two generations. For sustainable development, long-term behaviour - trends and structural changes - and stability issues at both the economic and ecological systems level are relevant for outcomes in the long run. Unfortunately, short-term adjustment processes after departures from equilibrium and long-term equilibrium trends and structural change are difficult to combine in one modelling framework. Models are either fitted to short-term data and are only adequate for describing short-term processes, or are orientated towards long-term data generated in the most accurate form (see Ayres 1978). The latter type of models will likely include very uncertain parameter values, functional forms and even relationships, for which scenario analysis must compensate. These models should be interpreted in a qualitative rather than predictive sense.

A social welfare function serves as an evaluation criterion for the identification of social decisions, which, in an ideal situation, can rank all possible social states. To aggregate individual utility functions for intergenerational comparisons the cardinal significance condition on utility functions is necessary, whilst also the choice of a discount factor may be considered³. One possible choice of an aggregate welfare function that is justified by different

³ Welfare of a generation is a quite vague concept. Besides the usual problems of aggregation of individual utilities additional ones arise in dynamic settings. First, it is important whether to think of the welfare of a generation in terms of a value at one point in time, or to approach it continuously. In the latter case one may take into account that a generation

moral systems (viz., Classical Utilitarianism and the Intuist conceptions; Dasgupta and Heal 1979), is the additive, separable utility function. For the case of continuous time the time horizon can be formulated as following a distribution with a probability density function $p(T)$, to reflect the uncertain exogenously determined time of extinction of the human race on earth. Then the additive, separable social welfare function may be generalized as:

$$\int_0^{T_u} \int_0^T \exp\left\{-\int_0^t \delta_s ds\right\} \cdot \sum_{i=1}^{L_t} u_i^t[x(t)] \cdot p(T) dt dT.$$

Here it is assumed that the discount rate δ_s , the number of individuals in the generation at time t L_t , and the utility function of individual i $u_i^t[\]$ may change over time. All relevant information on social states is incorporated in $x(t)$. The upper value of the time horizon T_u is regarded as finite. If T_u is infinite, the total integral may be replaced by one which has a finite value for T_u and is augmented with a bequest function or supplemented by conditions on stock variables at time T_u . A bequest function at time T 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 flexible generalization of a finite stock restriction. The bequest function or stock restrictions may apply to the stocks of capital goods, pollution and resources. Both such approaches bear much resemblance to the way decisions are made in reality.

An alternative welfare criteria is the maximin criterion based on the socio-ethical theory of Rawls (1971) or on the risk approach of Harsanyi (1955). The objective function to be maximized in this case is the minimum of the generational welfare over the period $t \in [0, T_u]$, with T_u certain and finite or infinite. This criterion concentrates on the welfare of the generation that is worst off. Substitution between generations' utilities - a highly possible consequence of the utilitarian criterion - will not be stimulated by this social welfare function.

exists for a period of positive length. This idea can be expressed by way of a function which explicitly aggregates the flow of welfare over a generation's lifetime. Furthermore, one may include the notion of overlapping generations.

For a society starting with poverty this means that it will endure poverty over all succeeding generations. This problem cannot be overcome with an extended 'maximin' principle, for example, by maximizing the minimum $U[C(i), C(i+1)]$ over $i \in N$, where i denotes the place in the total sequence of generations, and $N = \{1, 2, \dots, n\}$, with n the total number of generations living in $[0, T_u]$. 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).

A third general function for intergenerational evaluation can be derived from the idea of a penalty function based on planning targets. It is similar to one proposed by Tinbergen (1956) (and applied by Theil, 1964), although here applied over a longer time horizon:

$$\begin{array}{ll} \text{Minimize} & \sum_{t=0}^T w_t * [U_t(x(t)) - U_t^*]^2, \\ \{U_t^*; t \in \{0, 1, \dots, T\}\} & \end{array}$$

where $U_t(\cdot)$ is the welfare of generation t , $\{U_t^*; t \in \{0, 1, \dots, T\}\}$ is an a priori chosen desired utility path (i.e., the set of fixed targets), and w_t are weights (e.g., discount factors). In this case the choice problem is shifted from the evaluation criterion to specific welfare targets for intergenerational distribution. This still requires an explicit expression of the ethical convictions. If utility in the above functions is replaced (and targets accordingly) by other indicators, like pollution or resource stocks, other - though still intergenerational problems - are emerging. This targets based penalty function can also be regarded as a special case of the above mentioned utilitarian separable additive function, in which case the interpretation of the single terms (and similarly the U_t^*) in the sum is different, namely as indicators of a generation's welfare, instead of deviations from a given target.

Finally, ecologically oriented optimizing objectives may replace the above objectives, for instance: minimizing throughput (Daly, 1980); minimizing resource extraction; or minimizing pollution. They may be induced on the basis of naturalistic ethical considerations, or on recognising the relative importance of natural capital as compared to economic capital.

3.2. Discounting for intergenerational comparisons.

Discounting is a persistent issue in the discussions of intergenerational equity (see for instance Lind, 1982; Nijkamp en Rouwendal, 1988). Ethical objections against high or positive discount rates have focused on effects (see Opschoor 1987): shifting costs to later generations, and fewer incentives for long-term projects (especially environmentally favourable projects). However, a third consequence of low discount rates is a low development as a result of little investment in general. This may be environmentally beneficial because of its negative impact upon the demand for resources and emission of residuals (see Markandya and Pearce, 1988). So here the intergenerational equity and environmental objectives do not seem to completely agree⁴.

Discounting can only be applied if an additive, separable utility function is the criterion for multigenerational evaluation (benefit-cost analysis in an operational context). Therefore classical utilitarianism is at the basis of discounting. Discounting cannot be combined with a minimax criterion or social welfare functions with nonlinear or interaction components.

The basis for choosing a social discount rate has three dimensions: time preferences, investment opportunities and uncertainty considerations. If a social rate of time preference (consumption rate of interest) and a social opportunity cost rate can be determined, the social rate of discount can be derived as a weighted average of them, adjusted for risk by adding a 'social risk premium'. Two problems then arise. First, it is not evident how a specific choice of weights should be justified. Second, the estimation of the social time preference rate, the social opportunity cost rate, and the social risk premium poses some conceptual and practical difficulties.

The social time preference can be assumed irrelevant, when a community is not seen as showing impatience. Then individual pure time preferences are regarded as not transferable

⁴ Furthermore, if the total social outcome of private and social investments is evaluated by using a social rate of discount, a consistency problem may arise, as private investors will usually base their decisions on project evaluation on market rates of interest. Only for specific government projects a social rate may be used. Therefore, it is difficult to apply a social discount rate beyond the single project level.

to communities. Furthermore, conceptually there is a difference between discounting over relatively short periods (smaller than the average life-time) and over multigenerational time periods⁵. However, one may state that expected growth rates in consumption should be taken into consideration, as well as elasticity of the marginal utility of consumption, so that a positive time preference may result.

The opportunity cost will tend to be equal to the time preference rate in a perfect market, i.e. the market interest rate. This is one reason for concentrating on opportunity costs. A reason for focusing on the opportunity cost rate for social discounting derives from the difficulty to deviate from it: a higher rate will imply that fewer projects will be accepted; a lower rate may cause too many projects to be financed. The opportunity principle may also provide a relationship between the discount rate and the means of financing investments for a specific project. The discount rate may thus be set equal to: (1) The social opportunity cost rate, corrected for market imperfections and externalities, if the funds for a project are obtained from the capital market, or (2) the social time preference rate (consumption rate of interest) when consumption is sacrificed (taxes). Alternatively, costs and benefits with possibly varying social rates of time preference may be used (see Gijssbers and Nijkamp 1988). However varying rates over different investment projects may cause the problem of financial crowding out. Finally, the opportunity cost principle may apply only to small scale, short-term projects, while if extended to big-scale, government or long-term projects it should only be compared with other long-term projects, so that lower values of opportunity cost rates result. For, both types of projects have to be carried out and should not compete too much with each other, which may imply a minor role for the discount rate.

Including 'pure' risk in the discount rate is very restrictive (and stronger for other types of uncertainty), as it offers only one way of handling risk, namely as a negative exponential course (see Markandya and Pearce, 1988). Even if risk 'increases monotonically', it is very unlikely to be compatible with a negative exponential pattern. Therefore, more flexible

⁵ Remember that a positive discount rate implies a finite horizon. This is usually too large to be of any importance for short period considerations. However, over multigenerational periods it has much relevance.

frameworks are necessary (see section 6).

The above discussion indicates that there are potentials to minimize the attention to discount rates in discussions of intertemporal and intergenerational distributions. Then we have to agree that time preference applies only to individuals, not to communities or in any case not for multigenerational evaluation. Risk can be dealt with more appropriately in other ways than by adjustment of discount rates. Thus, only the opportunity cost principle has to be regarded, thereby taking notice of the remarks made above with respect to its use. The other aspects mentioned can be left out or incorporated in other ways, including possibly also external and intangible effects. The major advantage of a multi-purpose discount factor is that it simplifies the model structure.

3.3. Intergenerational constraints.

In addition to an evaluation criterion, intergenerational considerations may imply the inclusion of constraints in a model, referring to inter alia: values of state variables at T ; stocks, stock changes, or controls; and, integrals or sums over time of variables or functions of variables. Flow conditions may be derived from stock conditions.

For intergenerational comparisons 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 processes in reality are subjected to different speeds of internal dynamics and feedback loops, which means that actually the distinction of variables into stocks and flows is somewhat artificial. Since this is especially relevant in cases where long term horizons are employed, several types of flow may be used in intergenerational models.

Intergenerational aspects can be taken into account by including conditions on initial and final values of state variables in a model. If the time horizon T is finite 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 social welfare over

some finite time period. 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. The problem is shifted to the ethical dilemma of setting the stock conditions for some future point in time.

A second way of capturing intergenerational aspects through constraints is by formulating side-conditions on control variables and changes in stock values. For example, consider a biotic resource that is used for economic purposes. Suppose that its dynamic behaviour can be described by the following equation $\delta y/\delta t = F(y) - h(t)$ in which $y(t) = y$ denotes the total biomass. Now $\delta y/\delta t$ is the net change in biomass, resulting from natural growth according to the rate $F(\cdot)$ and from harvesting at a rate $h(t)$. The well-known notion of sustainable use of a renewable resource in this case would hold if the side condition $\delta y/\delta t = 0$ would be satisfied all the time. Theoretically this can easily be coped with. However, safety margins may be desired to account for the uncertainty surrounding the determination of the stock levels and dynamic behaviour of a renewable resource. To include safety margins an inequality condition should be derived. In the example above one may impose the condition $y \geq \epsilon > 0$ which leads to a constraint on the extraction rate $h(t) \leq F(y) - \epsilon$.

Meaningful conditions may also be included by imposing upper or lower bounds on integrals. First, the objective might be changed from maximizing an integral function (e.g., for indicating social welfare) to the requirement that it 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 modelling framework in many ways. Some of the approaches are overlapping in terms of description or effect, and therefore a complementary combination should be aimed for.

4. Regional models for sustainable development.

In view of the need for operational policies a meso level of analysis that is also in agreement with administrative possibilities is desirable. A meso level has the following advantages: interactions and feedback mechanisms are easier traceable than at a global level; environmental decisionmaking can easier be guided by a regional governmental agency; and, regions have specific problems or capacities that should be dealt with in their right context and level of detail. 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. To combine the two one may try to minimize economic-demographic and physical-ecological flows.

The two main differences between a global or closed and a regional or open system are that the latter is subjected to cross-boundary flows and has external determinants of internal processes. The cross-boundary flows can be distinguished into monetary-economic and physical-ecological. The external determinants have consequences for regional development. One region may be modelled separately, conditional on certain assumptions with regard to these flows and determinants. For sustainable development one of the following requirements may be imposed upon specific types of flows: (1) balance of material cross-boundary flows at each point in time; (2) closing internal and external flows through cross-boundary flows; (3) no cross-boundary flows. The external determinants can be based on specific development patterns assumed outside the region, which fit in the structure of a sustainable development of the multiregional system. Furthermore, in a multiregional context one is in principle free

to pursue policies of interregional distribution, or compensation of negative environmental effects of regional development may be extended to a multi-regional setting (leading to the notion of complementary development). If more regions are involved in such a way we obtain a top-down approach, in which supply and demand are cleared at the national level (see Issaev et al. 1982).

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 forced by national constraints on the behaviour of regional authorities, or by bargaining between regions (see for an operational example Alcamo et al., 1990). In order to deal with the spatial equity problem, one may set a minimum level for the total regional welfare by using appropriate indicators (e.g., income, natural vegetation, resources and pollution per capita or per m² regional land).

5. Multiple use and models.

The fact that populations, natural resources, or ecosystems may have many 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. Often however, activities do interfere, be it in a competitive or complementary way. Here we are considering the concept of multiple use, which can take different forms. First, ecosystems, populations and resources may provide similar services for both natural and economic activities. An example is a species functioning both as a prey for a natural and a human predator (e.g., some fisheries). Second, resources may be used by many individual human actors in a similar manner. Specific types of problem may then arise, namely congestion and inefficient outcomes, such as in open-access or common-property uses of an area, ecosystem or population. Their solution may require a social agency that controls the resource and its use. Third, the services rendered by natural

systems or resources to human actors may be very different, so that conflicts may result between users with very different goals. Examples of much occurring cases are the conflict between recreational and commercial uses of lakes, forests or fisheries. The social advantages of such activities may then be compared to arrive at a solution. Finally, various types of functions and qualities may derive from a resource system that are potentially beneficial in different ways for both human actors and ecological processes. An example is a forest that provides timber, recreational facilities, a stable flora and fauna, regulation of precipitation and evaporation of water, assimilative functions, a reservoir for pollutants, etc.

In using or affecting a resource base, economic activities and natural processes may be independent, competitive (the most extreme case is mutual exclusiveness), complementary or commutative. Many such multiple use phenomena can be dealt with by formulating models that include systematically the different potential uses and potential ecological and economic effects. Thus (potential) conflicts between uses and scope for trade-offs between them are adequately represented. By combining the economics and ecology of a multiple use problem it can be stated in a general form. One option is to determine the optimal combination of human activities (by benefit-cost analysis) constrained by the required levels of natural functions, the interactive economic-ecological flows and effects, and the internal dynamic processes of the ecosystem. A second general formulation of multiple use is in the form of a multi-objective programming problem, with each economic and ecological activity or function generating one or more objectives.

Multiple use can be regarded as a transitional approach to sustainable development, which is situated in between the single use of a single resource and the economically and ecologically interwoven patterns of multiple use of multiple resources.

6. Long term uncertainty.

The relationship between studying sustainable development and dealing with uncertainties is mainly related to the long time horizon and the economic-ecological interactions. Typical for long term issues is first that the combinations of events with a small likelihood of

occurrence and a significant long term impact are to be considered seriously. Second, there is a strange relationship between time and uncertainty. Over both very short and very long time periods the final outcome is, by and large, more predictable than for periods of intermediate length. Third, the nearer in time uncertain events are, the more seriously they are regarded. Distant, long term uncertainty is usually perceived with reservation. Faith and hope for intermediate solutions and favourable turns support this stance.

Especially important in a long term framework is the existence of social risk, i.e. the risk that is correlated between individuals (for instance, environmental catastrophes). It is not possible to be insured against such risk, as it cannot be allocated. Furthermore, in the long term many risky events - which are independently occurring over shorter periods - are dynamically correlated. Finally, much uncertainty emerges from unforeseeable qualitative 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. In such cases sustainable development 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.

A taxonomy of uncertainty includes certainty, risk, 'pure' uncertainty, and surprises. Certainty means that the outcome is sure and known. Risk means that the (range of) possible outcomes (is) are known, but their occurrence is uncertain and indicated by an objective or subjective probability distribution. In the case of 'real' uncertainty only the possible events are known, not their probability distribution. Finally, a surprise denotes an event not expected *ex ante* with any reasonable insight.

Classifying phenomena and events with respect to importance for uncertainty in long term sustainable development can be distinguished into three kinds. First, the existence and size of future generations is uncertain. Second, the economic phenomena of changing preferences and technological progress are very uncertain. But, it may be added that basic needs will not be different from ours. Third, environmental and ecological phenomena as well as stock values are uncertain. The exact stocks of renewable and non-renewable resources are

unknown. Ecological processes are uncertain, although there seems to be insight into some long term patterns. Little is known about the sensitivity of ecological processes to stress factors, such as various types of pollution. Also, the human health consequences of pollution are not completely understood. Finally, natural hazards (earthquakes, storms, flooding, volcano eruptions) are difficult to predict.

Two economic elements of approaches to uncertainty are attitudes and informational activity and valuation. For dealing with risky states of nature a special preference theory is available, based on utility functions that represent the attitudes of people towards risk, i.e. loving (risk taking), hating (risk averse) or neutral. Risk functions are combined with these utility functions to determine the expected utility. 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, namely 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, an option value is a conditional value of information and exceeds (or equals) the unconditional value of information. It allows for making a trade-off between the cost of waiting and of irreversible development.

Uncertainty can be regarded in terms of characteristics of the system of economic and ecological intra- and interactive processes. This will be most relevant for the present study. Timmerman (1986) distinguishes then five patterns (or views) of behaviour: (1) perfectly stable, (2) resilient, (3) cyclical, (4) switching between multiple stability points, and (5) catastrophic. The uncertainty surrounding the future behaviour of the system may thus be related to its complexity, the number of equilibria, the changes in the equilibrium states (e.g., through evolutionary processes), interrelated cyclical processes, non-linear phenomena, margins of resilience, instabilities, irreversibilities and chaos. Furthermore, the simultaneous occurrence of evolutionary patterns, trends, instable behaviour, and fluctuations leads to a confusing time series picture, which cannot be flawlessly separated as a result of insufficient

quality and quantity of data.

Some general rules can be given for handling long term risk. Risk averse behaviour is suitable if we understand the uncertainty well enough. For instance, if we deplete a non-renewable resource and are uncertain about its reserves, a low rate of use may be strived for to encourage a smooth transition to a renewable resource substitute, or a change in demand for it. Postponing critical situations may result by stimulating inventions and innovation, technology adjustment, substitution of production inputs and final goods, and changing preferences. Whether one may learn from surprises depends on their character. If they arise in the form of a system breakdown, it is impossible to gain something out of it, and similarly, if they are too small to be noticed or not recognized as important. In other cases we may learn from them and adjust our behaviour.

For a choice of tools to be used for implementing risk into scientific analysis one may choose between sensitivity analysis (with respect to initial and end conditions on state variables, parameter values in objectives, state transition equations and constraints), probability analysis (low probability/high impact analysis; Monte-Carlo experiments), or decision theoretic models.

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. Different types of model structures (relationships and specifications) may be investigated in this respect. 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).

7. Economic-ecological integration: dynamic models.

The economy and ecology are not merely different objects of study, but have also generated separate disciplines. This means that many of their theoretical concepts and methods are different. Also, the techniques used to operationalise theoretical concepts, or to perform empirical studies, and test hypotheses are not always similar. However, some correspondence can be observed as well, for instance, between the sub-disciplines dealing with a rather aggregate treatment of subjects of study, namely macro-economics and synecology, in both of which the method of deduction has dominated (see Van der Ploeg, 1974). Furthermore, although experimenting is limited in both fields, ecology possesses more opportunities for this than economics. A rational approach to integration is the use of formal models, in which processes of both fields are described and related to each other (see Brouwer, 1987). Methodological differences are circumvented to a certain extent this way, while the specific accumulated disciplinary knowledge is used to establish the structure of the model, select the elements and specify their relationships (see Braat en van Lierop, 1986). It is clear that then the simultaneous consideration of environmental problems or economic-environmental interactions is possible. The type of model that is relevant for gaining insight into sustainable development issues, or for tracing sustainable development paths, should satisfy a set of minimal requirements. The following considerations may clarify this:

(1) A complete or general - in contrast to a partial - approach should be taken, because it is relevant for long term horizons. The entire economic structure should be included in some way and the description of the natural environment should be compatible with it in the long run.

(2) The impacts of economic productive and consumptive activities upon the natural environment, in terms of materials extraction, waste emission and pollution, and non-material disturbances. In more detail one has to pay attention to (i) extraction of non-renewable and biotic and abiotic renewable resources, (ii) agricultural activities affecting groundwater and soils like fertilizing, use of pesticides, irrigation, drainage, ploughing, (iii) the use of terrestrial and aquatic ecosystems for recreational purposes, (iv) land use, and the patterns and

infrastructure involved, and (v) pollution and waste disposal, with a special notice for toxins, reactivity, dispersion, degradability, and also specific types such as thermal, radiation and noise pollution.

(3) The presence of a feedback from the ecology to the economy. This includes various elements related to for instance recreation and tourism, landscape values, quiet and annoyance. Inclusion of feedbacks of ecological impacts of general economic activity to the economic system is essential for an adequate description of long term processes in economic systems. For instance, feedback to decisionmaking with respect to productive activities may be included among other things via perception of resource scarcity, and pollution levels, or environmental damage in general.

(4) Not only material or priced services should be included, but also, as much as possible, other services, such as for instance productive conditions (e.g., soil quality) and amenity services. The latter may be included in the evaluation or welfare function, but equally by way of behavioural feedback mechanisms. All multifunctional aspects of ecosystems can be thus be dealt with.

(5) Concern for future generations must be included. First, this may imply that a judgement criterion is chosen for the evaluation of intergenerational distributions. Also various conditions may ensure an equitable intergenerational distribution. If the repercussions of intergenerational concern are taken in a behavioural - rather than an evaluative or constraining - sense it implies that behavioural or policy feedbacks aiming at intergenerational equity are endogenous.

(6) A long time horizon is a logical consequence of the foregoing point. It means that short term processes are whenever possible left out to simplify the picture. Also it implies that linear models will not be adequate for a description of every process, and that scenario analyses may be used for dealing with various possible strategies and policies. Furthermore, comparative static and dynamic analyses are relevant in the context of sustainable development. For instance, changes in tastes may be reflected by shifts in parameter values in the welfare function, or biological and ecological evolution by changing ecosystem

parameters.

(7) It should be possible to describe qualitative (structural) change, either implicitly or explicitly. This means that one has to allow for a description of irreversible processes, thresholds, nonlinear structures and time delays. This options may be supplemented by risk analysis to deal explicitly with uncertainty in various ways.

(8) The model assumptions should not conflict with physical constraints. Conceivable limitations on substitution in production and utility functions should be built in. Furthermore, interdependencies between substitution of production factors, investments and technological progress have to be considered simultaneously. Model assumptions should not conflict with thermodynamic laws. Material balances can be included explicitly.

(9) As regards specific sustainable development conditions, we distinguish between constraints on the level of welfare (for a whole generation or per capita) over generations and restrictions on physical-ecological stocks and flows. In the first case one may choose between the following types of conditions⁶: (i) requiring welfare always to exceed some minimum level (e.g., a subsistence level), or (ii) requiring a monotonous non-decreasing movement of welfare over time. The second type of conditions may involve constraints on stocks or on flows in and between economic and environmental systems. For instance, the notion of stock constancy (or non-decreasing stocks) may be applied to the sum of man-made economic and natural stocks, to a stock concept such as environmental quality or environmental degradation, to the sum of all natural stocks (compensation principle), or to each stock separately. Instead of directly applying such stock conditions to a model one may use derived flow conditions.

These considerations point out that the dynamic element is essential. A second important implication is the need for joining environmental-ecological and economic processes in these models. The terminology 'economic-ecological' has been used to denote models that

⁶ Pezzey (1989, p.13) gives a systematic account of possible simple formulations in this respect. He further links it to the distinction between combinations of on the one hand growth, development and resource use, and on the other hand survivability and sustainability.

implement very different concepts of integration. It has been employed for economic process models which include environmental variables (e.g., waste emission or resource extraction) and ecological process models with economic variables (e.g., stress factors). The considerations mentioned above indicate that a stronger concept is necessary to deal with sustainable development, namely one that integrates economic and ecological processes instead of an economic process and an isolated exogenous ecological variable (or the reverse).

Modelling for sustainable development may require that many relationships are specified. First, it involves subjective decisions with regard to crucial variables. Second, as a result of lack of knowledge and data each relationship is surrounded by uncertainty. With many relationships, this may then severely impact upon the reliability of the whole model in a negative way. Finally, it is clear that some processes and problems inherent to sustainable development cannot be dealt with properly by way of analysis with mathematical models. However, in many cases where well-performed modelling studies fail to augment our insight, other approaches often suffer from the same failure.

8. Summary and conclusion.

Modelling integrated ecological-economic systems for sustainable development should be preceded by a thorough reflection on the concepts to be used. In this paper we have tried to do this in a systematic manner. As intergenerational aspects we have reckoned the choice of the time-horizon, a criterion for multi-generational welfare comparisons, the intergenerational discount rate and constraints on stocks, flows or integral functions. A target approach and optimizing objectives with a focus on ecological indicators were mentioned as alternatives to the usual intergenerational evaluation criteria based on Utilitarian and 'Rawlsian' ethical theories. It is argued that the significance of discounting for intergenerational purposes may be limited. A main difficulty may be the difference between the evaluation of single private and social projects and development in general over periods of multigenerational length. Constraints may replace or complement intergenerational evaluation criteria. One may choose between stock conditions and bequest functions, use ecological (effect) conditions or transform these into activity constraints. Integral functions may be constrained over certain periods, and may replace optimization objectives.

Models on a regional scale are likely to be very relevant for the purpose of operational studies and policy analyses for sustainable development. They require that attention be given to two main elements: cross-boundary flows and external determinants. For sustainable development one may require a combination of conditions, possibly different for various monetary-economic and physical-ecological flows. These conditions may be as follows: A balance of flows is established at each point in time; or, internal and external flows are closed, so that a balance over some period holds; or, no cross-boundary flows in one or two directions (even if a balance can be established).

Multiple use can be formulated as a problem of finding the combination which is optimal in terms of a constrained cost-benefit analysis. Static constraints represent limits to interactive economic-ecological flows. Dynamic constraints describe internal dynamic processes of the ecosystem. A second formulation uses a multi-objective programming design. Each sufficiently relevant economic and ecological activity or function corresponds then to one or more

objectives. Multiple use models are an intermediate between single resource models with a partial view and complex economic-ecological models with a general view.

Long term uncertainty can be handled with the usual techniques such as sensitivity analysis, dynamic analysis, stability analysis, Monte-Carlo experiments, and other type of probability analysis or decision theoretic models. However, most of these assume that we deal with risk or can at least say something about probabilities involved. The real interesting type of uncertainty that is likely to arise over longer periods is the surprise. It can be discovered by performing scenario analysis and by determining the dynamic characteristic of systems, such as related to stability and chaotic behaviour. However, empirical knowledge must feed into models to improve our understanding of processes and probabilities, so that we can transform important surprises into a risk structure.

Much scientific support has been given to the aim of economic-ecological integration since the world-wide concern with sustainable development. What it actually means in a methodological and operational sense, is usually unclear. In the last section we have argued that formal models may offer some new perspectives. Such integrated models are also relevant as tools for sustainable development, provided that in any case the nine requirements mentioned in the last section are satisfied. Important is that economic-ecological integration should be understood in a very precise way, namely in the sense of integrating economic and ecological processes rather than a process and an exogenous variable. This paper has suggested ways to formulate and use models. The next step is to develop them in a specific empirical context. This will then also allow for a test against the real world patterns that arise with or without specific measures directed at establishing sustainable development.

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